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ENERGY EFFICIENT ENGINE  
COMBUSTOR COMPONENT PERFORMANCE PROGRAM

by

D.J. Dubiel

UNITED TECHNOLOGIES CORPORATION  
Pratt & Whitney  
Engineering Division

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## FOREWORD

The Energy Efficient Engine Component Development and Integration Program is being conducted under parallel National Aeronautics and Space Administration (NASA) contracts with Pratt & Whitney Group and General Electric Company. The overall project is under the current direction of Mr. Carl C. Ciepluch, with the Pratt & Whitney effort under contract NAS3-20646. Mr. Daniel E. Sokolowski is the NASA Project Engineer responsible for the portion of the project described in this report. Mr. David E. Gray is the manager of the Energy Efficient Engine program at Pratt & Whitney Group, with Messrs. D.J. Dubiel, W. Greene, and S. Tanrikut, the engineers responsible for work described in this report.

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## SECTION 1.0 SUMMARY

The objective of the Combustor Component Performance Test Program was to demonstrate the aerothermal and environmental goals established for the Energy Efficient Engine Program and to identify areas where refinements could be made to meet future combustor requirements. Two performance tests were conducted: the first, a full annular combustor test rig and, the second, the 1.57 radian (90 degree) combustor sector test rig. The first test was performed to establish emission levels and combustor performance for comparison with those from the previous sector rig efforts, Reference 2. The primary purpose of the second performance test was to examine those differences in emissions and liner temperatures between the full annular performance test and the previous supporting technology tests.

The combustor design was derived from an earlier generation low emissions Vorbix combustor with several modifications made to improve smoke emissions and combustor durability. Full annular and combustor sector test rigs were fabricated to functionally simulate the design intent. They were installed in experimental Pratt & Whitney test stands with a variety of test instrumentation to monitor operating conditions and ensure an accurate characterization of combustor performance.

Parametric variations of combustor fuel/air ratio were investigated at all operating conditions with the full annular rig. The optimum fuel distribution between the pilot and main combustion zones was established. The exit temperature radial profile goal for the full annular combustor was achieved. Pattern factor below goal was also demonstrated. Emissions levels increased compared to levels demonstrated in sector rig testing with sheet metal carburetor tube, Reference 2. These differences were shown in the subsequent sector rig test to have resulted from the higher flowing cast carburetor tubes utilized for the first time in the full annular rig. Modifications to the carburetor tubes aimed at returning emissions to previously demonstrated levels were evaluated in the combustor sector rig. Results of these tests indicated that previously demonstrated emissions levels could be achieved with reduced flow cast carburetor tubes.

The combustor sector test run in this component program verified that significant reductions in inner liner temperatures were achieved with the cast carburetor tube design. These observations, based on thermal paint analyses, substantiated the improved liner temperature patterns observed in the initial full annular rig test.

A very significant result of this program was the evidence supporting the combustor sector rig as a reliable indicator of full annular component performance characteristics.

## SECTION 2.0 INTRODUCTION

The objective of the Energy Efficient Engine program is to develop, evaluate, and demonstrate the technology for achieving lower installed fuel consumption and lower operating costs in future commercial turbofan engines. NASA has set minimum goals of a 12 percent reduction in thrust specific fuel consumption, a 5 percent reduction in direct operating cost, and a 50 percent reduction in performance deterioration for the Energy Efficient Engine (flight propulsion system) relative to the JT9D-7A reference engine. In addition, environmental goals on emissions (meet the proposed EPA 1981 regulation) and noise (meet FAR 36-1978 standards) have been established.

The Pratt & Whitney program effort is based on an engine concept defined under the NASA-sponsored Energy Efficient Engine Preliminary Design and Integration Studies Program, Contract NAS3-20628. This program is discussed in detail in Reference 1. The Pratt & Whitney engine is a twin-spool, direct drive, mixed-flow exhaust configuration, utilizing an integrated engine-nacelle structure. A short, stiff, high pressure rotor and a single stage high pressure turbine are among the major features in providing for both performance retention and major reductions in maintenance and direct operating costs. Improved active clearance control in the high pressure compressor and turbines, advanced single crystal materials in turbine blades and vanes, and shroudless fan blades are among the major features providing performance improvement.

To meet the program objectives, two technical tasks were established by the Pratt & Whitney Project Team:

Task 1     Propulsion System Analysis, Design, and Integration

Task 2     Component Analysis, Design, and Development

Under Task 2, an advanced combustion system was developed for the Energy Efficient Engine. The goals defined for this system were the achievement of performance, emissions, exit temperature pattern factor, and durability consistent with the requirements established for the overall Energy Efficient Engine. Numerous advanced technology features and goals were demonstrated through a set of full annular and combustor sector rig tests.

A Supporting Technology Program (Reference 2), utilizing the 1.5705 radian (90 degree) sector rig, assisted in the selection of the combustor design by verifying needed technology. The combustor was then designed and fabricated followed by tests of the chosen design.

This report documents the combustor performance test program including full annular combustor component testing and related 1.57 radian (90 degree) combustor sector rig testing. The combustor component description is included in Section 3.0. A description of the test hardware and test conditions is contained in Section 4.0. Section 5.0 describes the test instrumentation, test facilities, and data acquisition systems. Test results are included in Section 6.0.

### SECTION 3.0 COMBUSTOR COMPONENT DESCRIPTION

The selected combustor design (Figure 3-1) employed a two stage, annular system having an advanced segmented liner and independent pilot and main combustion zones for low exhaust emissions and combustion stability throughout the operating range. The pilot zone minimized idle emissions and provided stability and good relight characteristics. The main zone provided fuel-lean combustion to minimize smoke and oxides of nitrogen at higher operating conditions. The two stage Vorbix combustor tested during the NASA Clean Combustor Program (Reference 3) formed the basis for the two-zone combustor design of the E3 combustor.

The segmented liners were fabricated from a nickel-base alloy (B-1900+H<sub>c</sub>) and featured Counter-Parallel FINWALL<sup>®</sup> cooling. Both the inner and outer liners were divided into segments (120 total) in both pilot and main combustion zones. These segments were supported by inner and outer structural frames. Hooks on the back of each segment engage with circumferential rails on the structural frame to position the segments. Liner segment life was estimated at 7200 cycles or 11,700 hours, where life was defined as the number of cycles or hours before a crack appears in the liner segment.

Fuel was supplied to the pilot zone through 24 aerated injectors and to the main combustion zone through 48 pressure-atomizing fuel injectors. The injectors were clustered on 24 support assemblies.

The curved prediffuser was used to align compressor exit air with the center line of the combustor and reduce pressure losses associated with flow turning in the combustor hood region. It was strutless, had curved walls, and was canted outward.

The diffuser case structural struts were designed to improve distribution of combustor flow and to improve liner durability and pattern factor. The combustor hood was positioned sufficiently downstream from the prediffuser dump plane to minimize overall prediffuser and annulus region pressure losses. The hood had sufficient plenum volume to provide high static pressure recovery and a uniform inlet airflow profile.

The pilot-zone had the same ratio of fuel injector spacing to dome height as in the Vorbix combustor. A proportionately larger recirculation zone improved relight and starting characteristics and provided a greater potential for reducing idle emissions. The pilot-zone heat-release rate was reduced (through lower reference velocity and higher pilot zone residence time at idle) to minimize the emissions of carbon monoxide and unburned hydrocarbons.

The main zone retained features for reducing the oxides of nitrogen demonstrated by the Vorbix combustor. The length of the Energy Efficient Engine combustor was reduced by removing the Vorbix combustor throat section between zones, to reduce cooling air requirements and to increase the probability of lowering high-power smoke emissions and improving combustor durability.

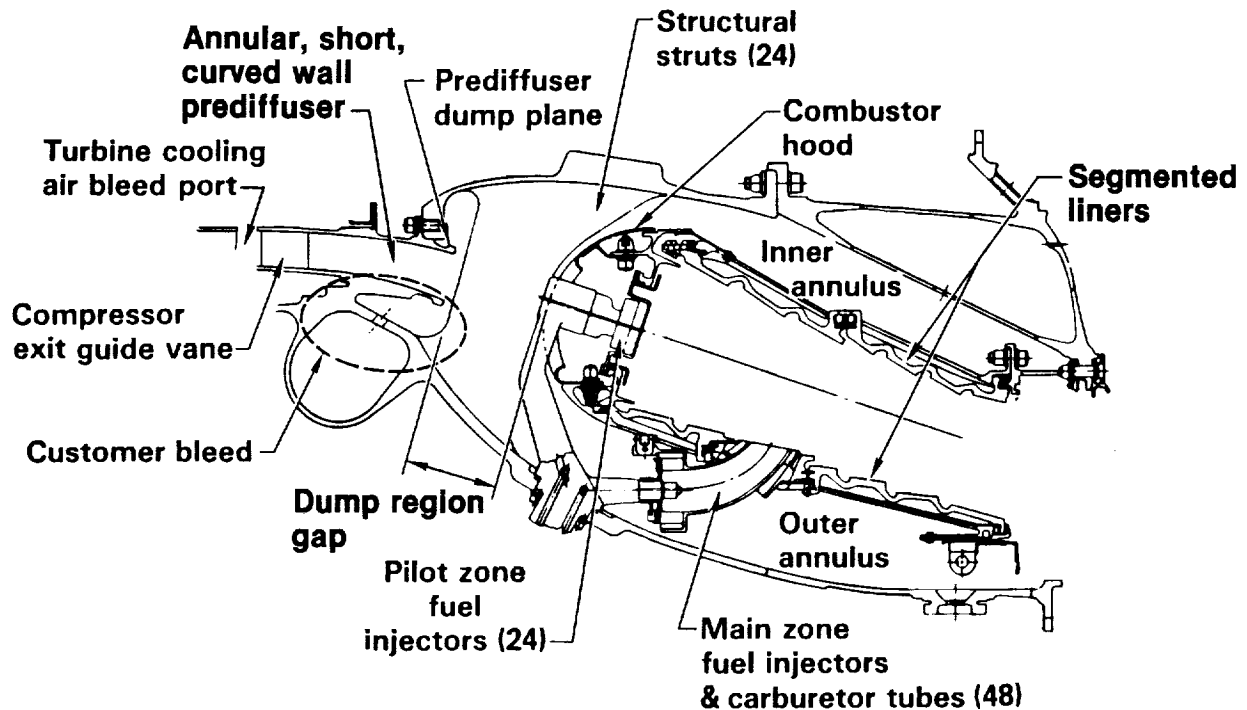


Figure 3-1 Energy Efficient Engine Two Stage Combustor Design Features

A compact carburetor type fuel injection system mixed fuel and air outside the main combustor zone to reduce smoke emissions. Carburetor tube air transported fuel into the main zone of the combustor to provide adequate fuel penetration over the entire operating range. Carburetor tube inlet air, introduced through separate swirlers in the Vorbix design, was introduced through radial inflow swirlers concentric with the fuel injectors in the Energy Efficient Engine design. The carburetor tube concept improved main zone fuel penetration and atomization characteristics over the entire range of combustor operation.

The airflow schedule for the full annular combustor configuration was established based on Supporting Technology Program data. The overall combustor was scaled down 12 percent from the supporting technology hardware size to reflect the current engine design. The carburetor tube design was also modified to improve castability and tube installation. The pilot injector design was essentially the same as the optimum indicated by the Supporting Technology Program.

SECTION 4.0  
COMBUSTOR COMPONENT PERFORMANCE TEST RIGS

4.1 FULL ANNULAR COMBUSTOR

4.1.1 Full Annular Combustor Component Performance Test Rig

A cross section of the full annular combustor performance test rig is shown in Figure 4-1. The rig incorporated the Energy Efficient Engine diffuser and combustor sections and the appropriate mounting and adapting hardware for installation into the test stand.

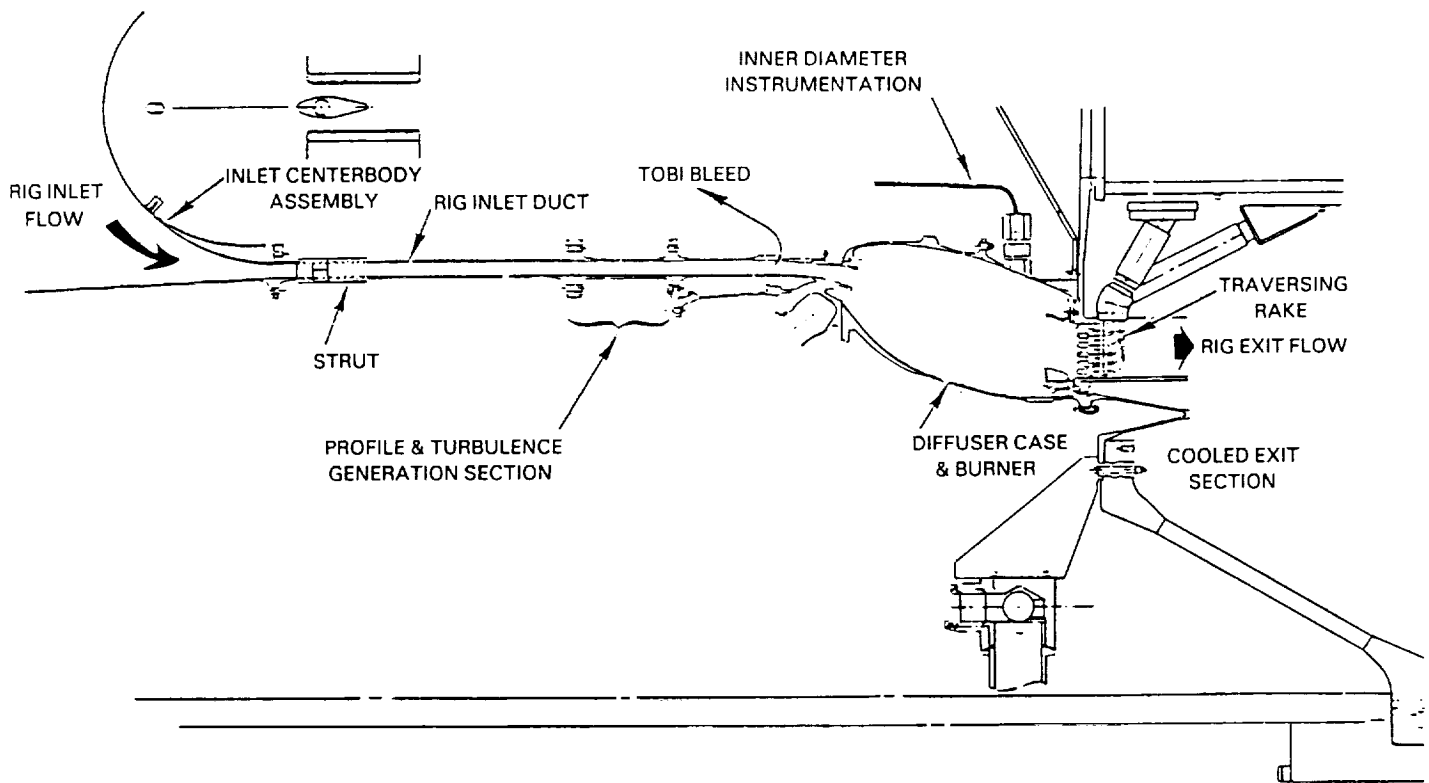


Figure 4-1 Cross Section of Full Annular Combustor Performance Test Rig

To provide test flexibility, the rig inlet section contained a removable profile generation duct that permitted testing with flow perturbations to simulate various compressor discharge profiles while the rig was installed in the facility. In addition, tangential onboard cooling air injection (TOBI) used for turbine cooling was realistically simulated. This air was taken at the prediffuser inlet.

Details of the full annular combustor and test rig hardware are shown in Figures 4-2 through 4-7.

A picture of the combustor inner liner support frame is shown in Figure 4-2 with some liner segments installed. Figure 4-3 shows the combustor bulkhead section mated to the inner and outer combustor liner support frames. Fuel manifolds and the sealing shroud are pictured in Figure 4-4 with the shroud cover removed. The assembled full annular combustor rig is shown in Figure 4-5 prior to being installed on the support diaphragm that connects the rig to a pressure capsule. Insulation blankets to reduce radiation heating of cooling air flowing in the annulus formed by the case outer walls and the rig capsule can be seen in the figure.

Figure 4-6 shows the pressure capsule. Quick disconnect panels for pressure sensors and multi-pin connectors for temperature sensors are mounted on the instrumentation ring, which facilitates mounting and removal of the test rig in the capsule. Figure 4-7 shows the rig before installation in the pressure capsule. Initially, the quick disconnect panels are installed after the rig is in place. However, after the panels have been installed, only plug-in connections are required for subsequent installations.

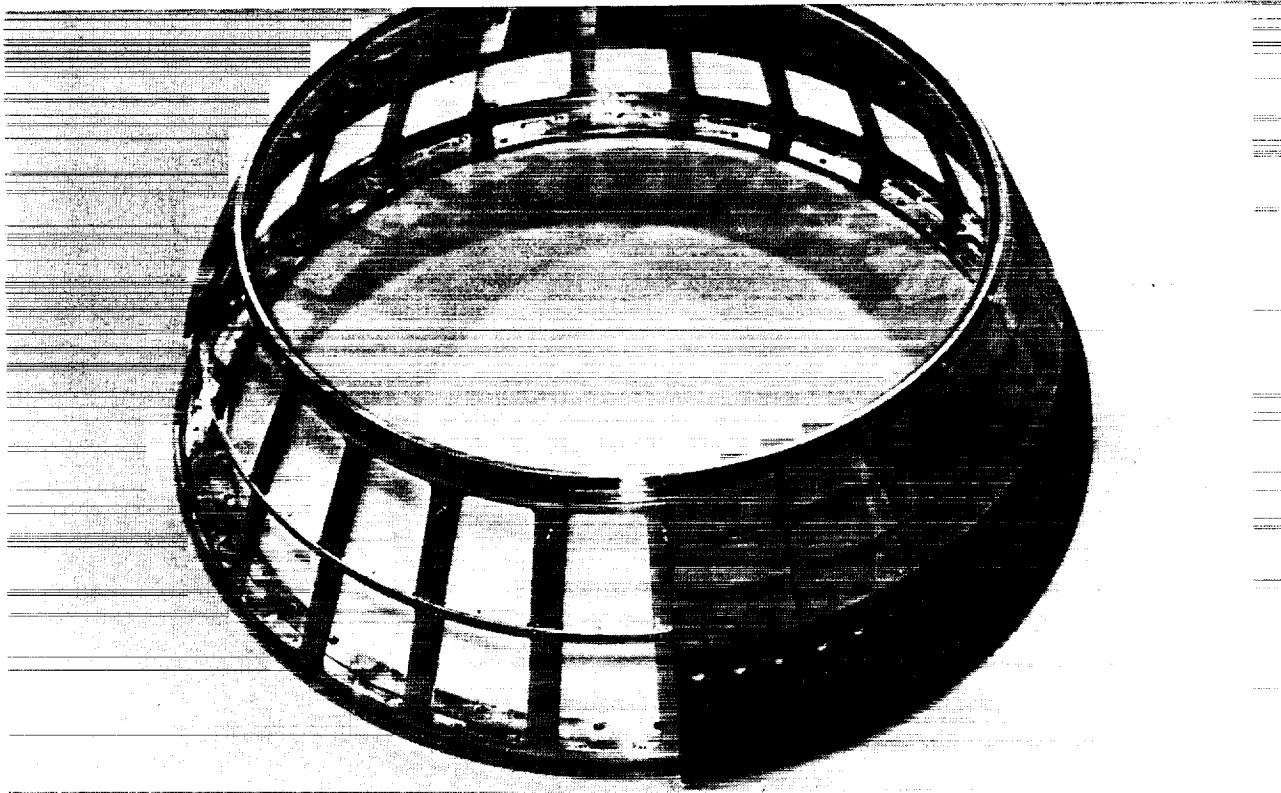


Figure 4-2 Combustor Inner Liner Support Frame Shown With  
Several Liner Segments Installed

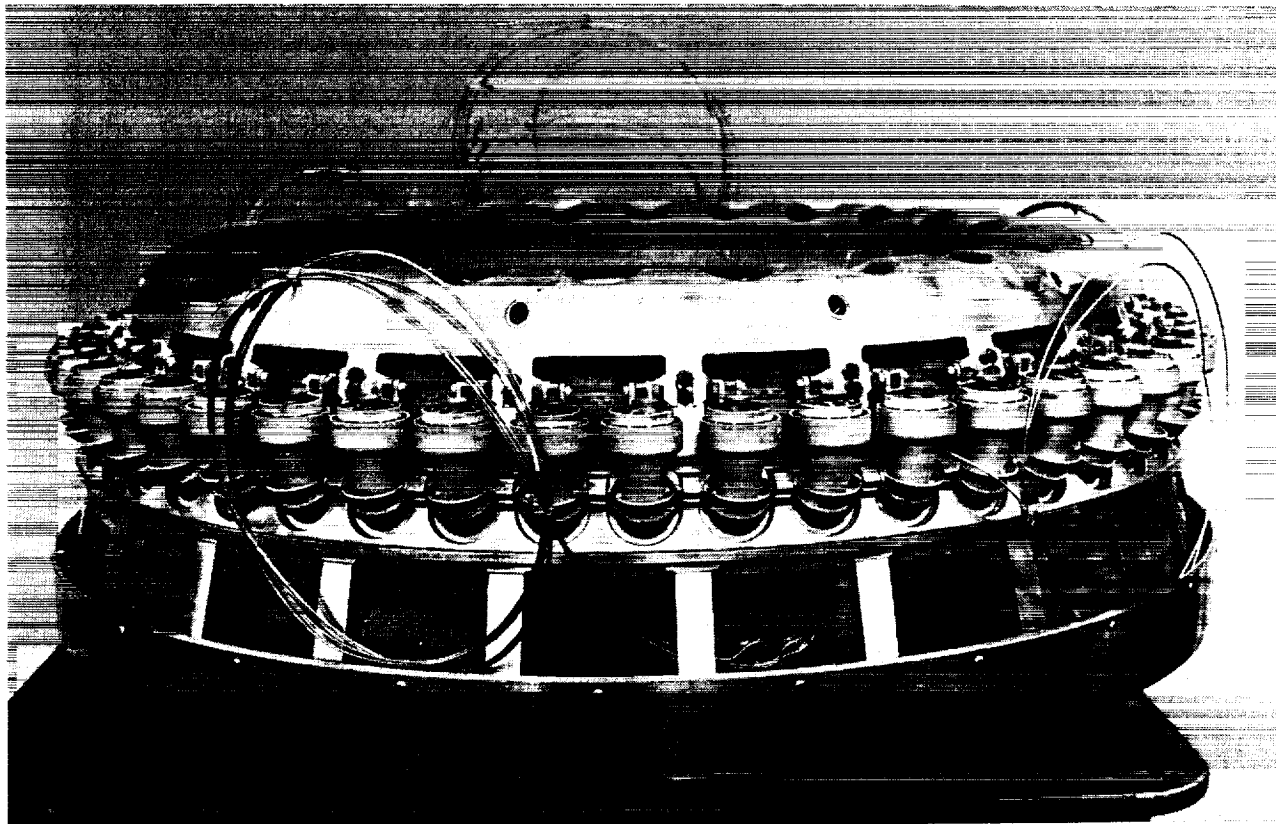


Figure 4-3 Combustor Bulkhead Mated to the Inner and Outer Liner Support  
Frames

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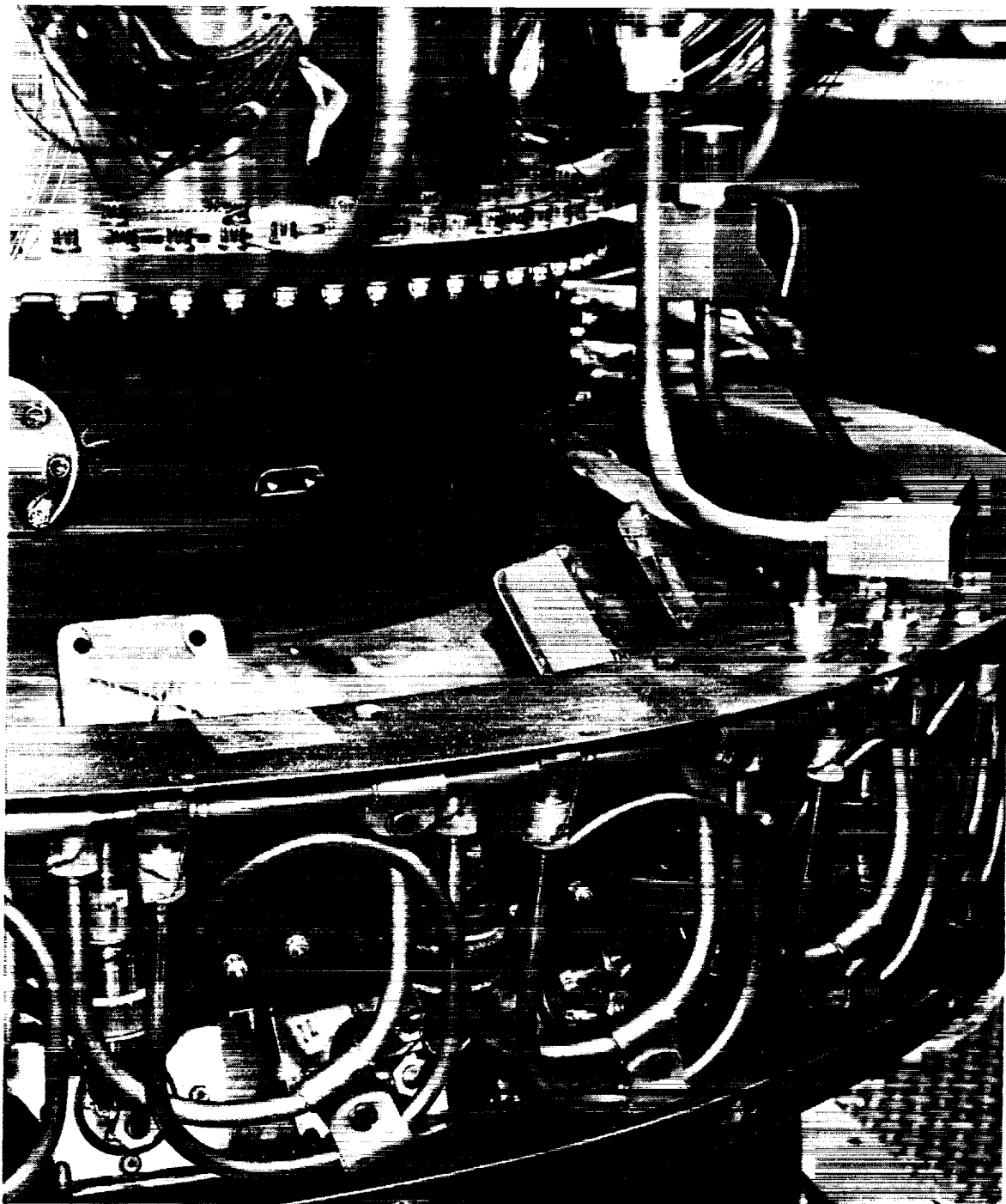


Figure 4-4 Fuel Manifold Sealing Shroud Shown Without  
Outer Cover in Place

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Figure 4-5 Full Annular Combustor Rig Prior to Installation Into Pressure Capsule. Insulation Blankets on Inlet Duct Reduce Radiation to Cooling Air Flowing Between Case Walls and Pressure Capsule

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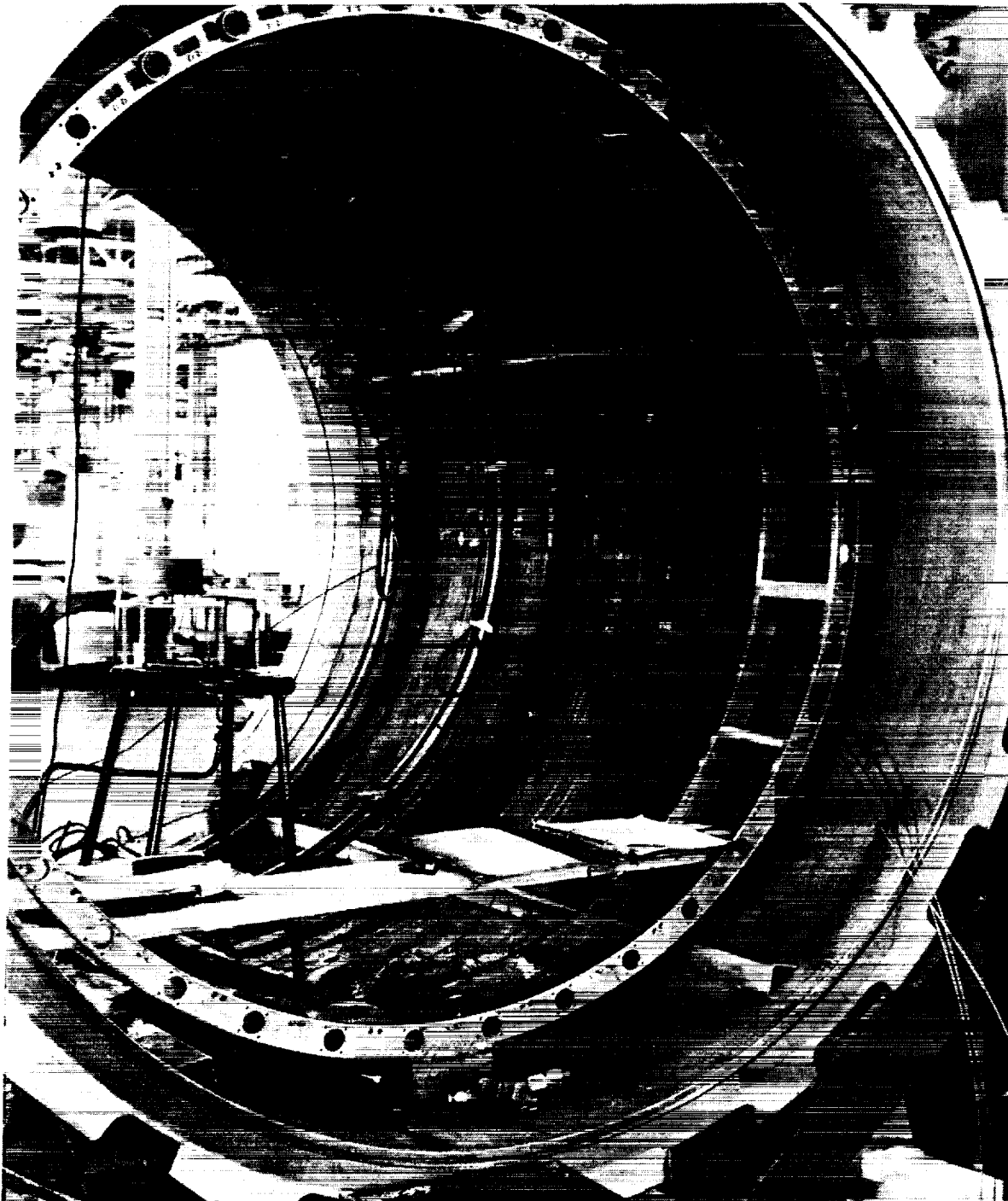


Figure 4-6 Pressure Capsule, Showing Quick-Disconnect Panels for Instrumentation Connection, Facilitating Mounting and Removal of Combustor Rig From Capsule

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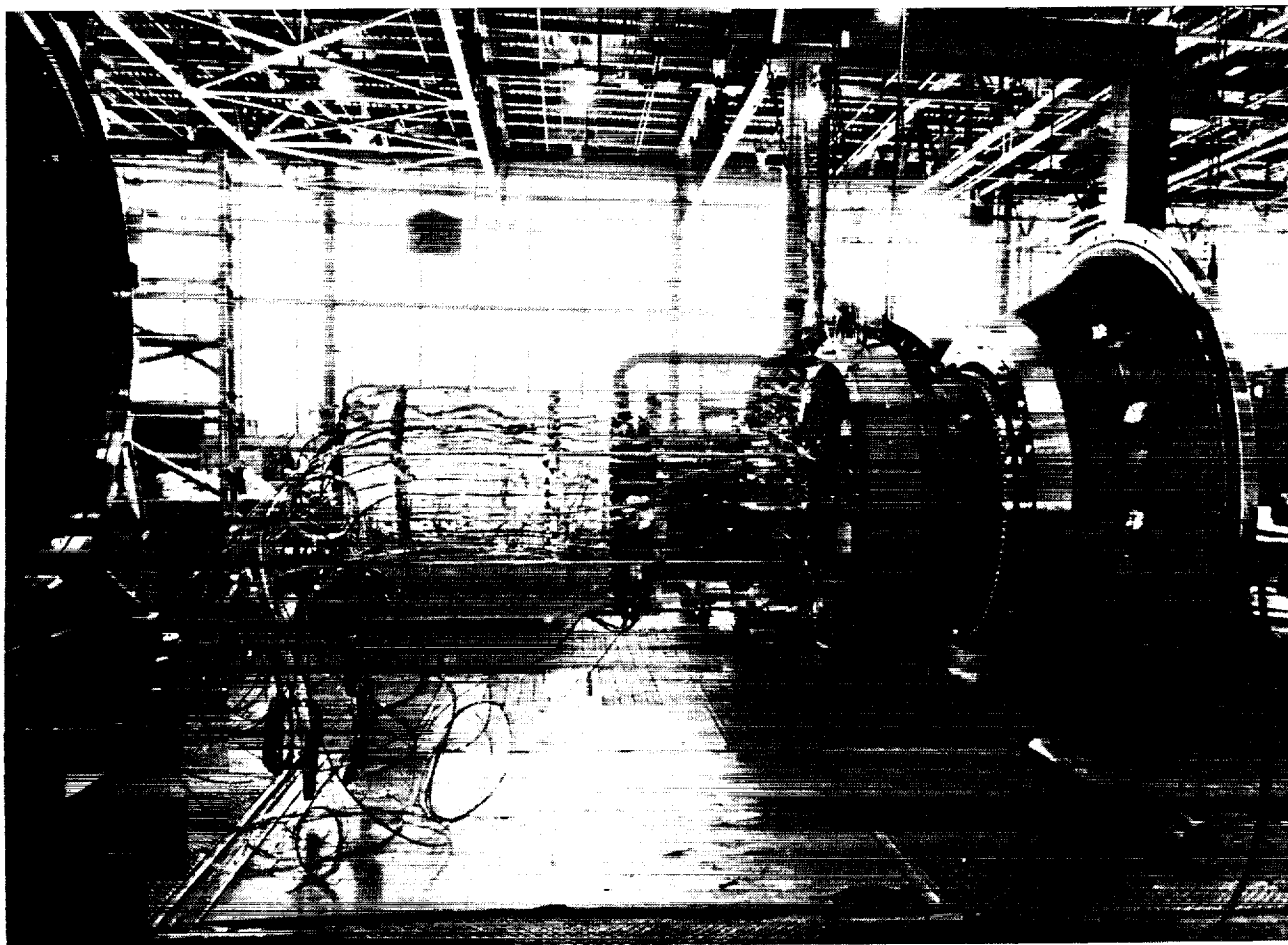


Figure 4-7 Test Rig Shown Prior to Installation into Pressure Capsule

#### 4.1.2 Full Annular Combustor Rig Test Conditions

The test conditions for the full annular combustor are listed in Table 4-I. These conditions matched the engine operating conditions specified by the Environmental Protection Agency (EPA) for calculating EPA emissions parameters. The operating conditions correspond to those anticipated for the Energy Efficient Engine. Parametric variations of the combustor fuel/air ratio were investigated at all operating conditions. The pilot-to-main-zone fuel split at high power was varied while the total fuel flow was held constant. The test data permitted the identification of optimum fuel distribution between pilot and main zones.

TABLE 4-I  
FULL ANNULAR PERFORMANCE TEST RIG CONDITIONS

<u>Condition</u>	<u>Combustor Inlet Press. MPa (psia)</u>	<u>Combustor Inlet Temp. °C(°F)</u>	<u>Combustor Inlet Flow kg/sec(lb/sec)</u>	<u>Fuel/Air Ratio</u>
Idle	0.434 (63)	199 (391)	13.6 (30.0)	0.0098
Approach	1.151 (167)	348 (659)	30.8 (68.0)	0.0150
Climb	1.862 (270)*	501 (935)	45.3 (100)	0.0230
Takeoff	2.068 (300)*	532 (991)	45.3 (100)	0.0250

\*Flow parameter simulation at facility-imposed maximum operating conditions.

#### 4.2 COMBUSTOR SECTOR RIG

##### 4.2.1 Combustor Sector Test Rig

The sector combustor test rig (Figure 4-8) duplicated a 1.57 radian (90 degree) sector of the full annular combustor. This simplification in construction substantially reduced the cost and down time for installation and removal or for modification of configurations. The construction was ideally suited for quick parametric studies of basic combustor trends while enhancing test flexibility, accessibility, and component realism.

The inlet section contained provisions for simulated tangential onboard injection bleed, simulated customer service/active clearance control bleed, and removable prediffuser walls. The inlet section also contained a profile generator that could simulate a variety of high pressure compressor exit conditions. The pilot and main fuel injectors could be installed separately for additional flexibility. At the combustor exit plane, instrumented vane packs allowed for the acquisition of pressure, temperature, and emissions data.

The sector rig configuration was nearly identical to that used during the Supporting Technology Program (Reference 2). The principal difference was that the reference 2 program featured combustor tubes fabricated from sheet metal, whereas this test configuration utilized cast carburetor tubes from the full annular combustor. The sheet metal concept facilitated modifications required to optimize combustor performance. The cast configuration was intended to reflect the optimum configuration derived from the reference 2 effort.

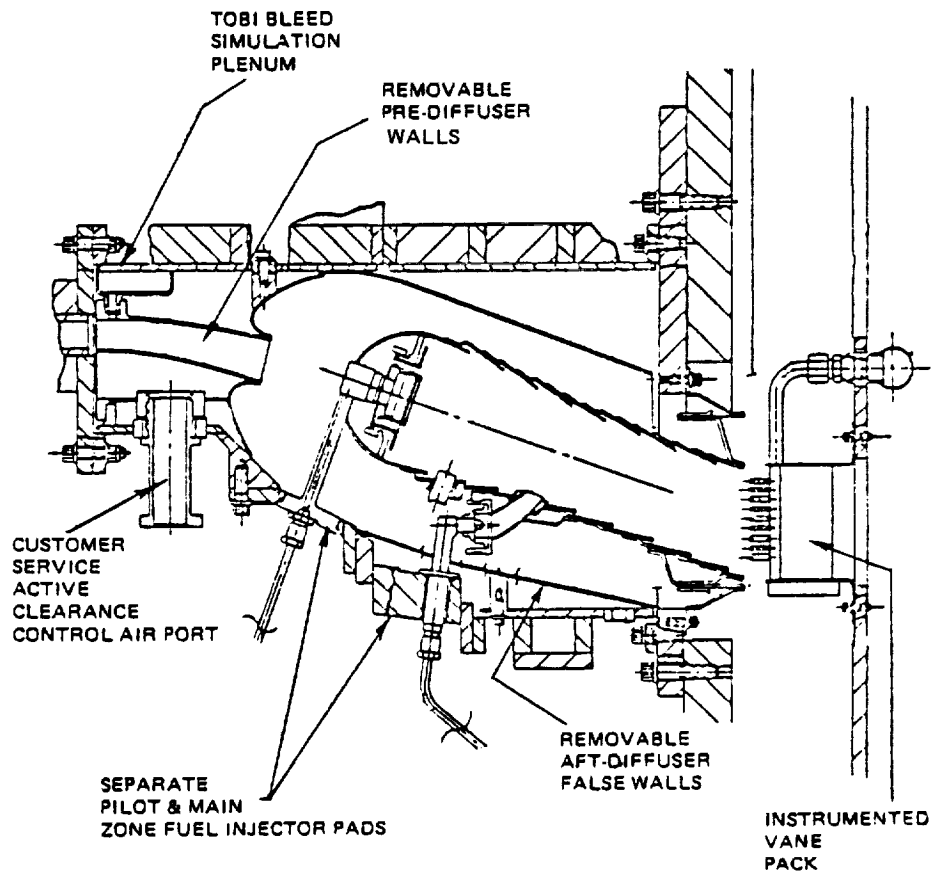


Figure 4-8 Combustor Sector Test Rig Cross Section

#### 4.2.2 Combustor Sector Rig Test Conditions

The sector combustor rig tests were conducted at the operating conditions indicated in Table 4-II. Parametric variations in the fuel air ratio were also investigated at idle and at the two high-power takeoff conditions.

TABLE 4-II  
COMBUSTOR SECTOR RIG PERFORMANCE TEST CONDITIONS

Condition	Combustor Inlet Pres MPa(psia)	Combustor Inlet Temp °C(°F)	Combustor Inlet Flow kg/sec(lb/sec)	Fuel/Air Ratio
Idle	0.434(63)	199(391)	3.4(7.5)	0.0098
Approach	1.158(168)	348(659)	7.3(16.1)	0.0150
Takeoff*	2.068(300)	532(991)	11.5(25.4)	0.0250
Takeoff	3.061(444)	532(991)	16.9(37.3)	0.0250

\* Reduced pressure takeoff condition.

## SECTION 5.0 INSTRUMENTATION AND FACILITIES

### 5.1 INSTRUMENTATION

Both full annular and sector performance test rigs incorporated a variety of instrumentation to monitor operating conditions such as inlet flow, temperature, and pressure and to record combustor performance, emissions, and structural characteristics. Imbedded thermocouples were installed in the liner to measure surface metal temperatures. The diffuser and combustor sections were sufficiently instrumented to ensure an accurate characterization of combustor performance.

#### 5.1.1 Full Annular Combustor Rig Instrumentation

##### 5.1.1.1 Performance Instrumentation

The full annular combustor rig was extensively instrumented at combustor inlet and exit locations with pressure, temperature, and gas-sampling sensors for documenting performance and emissions as shown in Figure 5.1 and listed in Table 5-I. Circumferential locations were selected to provide close monitoring of system performance within a small sector of the rig while ensuring overall uniformity of operating behavior. Six total pressure probes, six total temperature probes, and a series of wall static pressure taps measured combustor inlet conditions.

Combustor exit radial and circumferential temperature distributions and exhaust gas samples were obtained with a traversing multiprobe system. The system consisted of seven multielement probes. Five of the probes measured total pressure and acquired gas samples for determining total hydrocarbon, carbon monoxide, oxides of nitrogen, and smoke level. Each of these five probes had four radial sampling elements. The two remaining probes measured total temperature and had five radial sensing elements at the combustor exit plane in the same axial location as the first stage turbine vane. Figure 5.2 shows the total pressure, temperature and emissions probe assemblies. The probes were air cooled, and the gas sample lines were water cooled. The gas sampling lines were manifolded together so that emissions were averaged.

The data acquisition system included a combination of scanivalves and individual pressure pickups. Steady state pressures were recorded in the normal mode by transducers mounted in the scanivalves. Airflow was measured by two force balance transducers. A precision pressure gage measured the reference barometric pressure. Based on previous applications, pressure measurement tolerance of less than  $\pm 0.10$  percent of transducer full-scale pressure was predicted for steady state data. To ensure pressure measurement accuracy, a primary calibration of the high-accuracy, steady state transducers was performed prior to starting the test using dead weight testers calibrated against traceable standards of the National Bureau of Standards. A secondary calibration, which used at least two known pressures to each high-accuracy transducer, was available for updating the primary calibration curves during each data scan.

TABLE 5-I  
FULL ANNULAR COMBUSTOR PERFORMANCE INSTRUMENTATION

LOCATION	MEASUREMENT/TYPE	QUANTITY	PURPOSE
INLET	5 ELEMENT TOTAL PRESSURE PROBE	6	o RIG INLET $P_r/T_r$ PROFILES
	5 ELEMENT TOTAL TEMPERATURE PROBE	6	
	ID/OD WALL STATIC PRESSURE TAPS	4/4	
OUTER SHROUD	2 ROWS WALL $P_s$ TAPS HC SNIFFER	11 & 14 each row 5	o LINER FEED PRESSURE MAP o SAFETY
INNER SHROUD	2 ROWS WALL $P_s$ TAPS	14 each row	o LINER FEED PRESSURE MAP
COMBUSTOR HOOD PILOT NOZZLE INNER PASSAGE	$P_s$ TAPS $P_r$ KIELHEAD	9 7	o BULKHEAD FEED PRESSURE o NOZZLE FEED PRESSURE
EXIT	TRAVERSE RAKE 5 $P_r$ /SAMPLE HEADS TRAVERSE RAKE 2 $T_r$ HEADS	4 $P_r$ /GAS SAMPLE PORTS 5 $T_r$ PORTS	EXIT MEASUREMENTS

#### 5.1.1.2 Liner Temperature Sensors

One hundred and two thermocouples recorded liner metal surface temperatures. Thermal-sensitive paint was also used on selected liner panels to assess liner thermal gradients. Seventy-eight thermocouples were located on the inner liner and twenty-four on the outer liner, as shown in Figure 5-1. The thermocouples were imbedded in the liner to record hot wall surface metal temperatures and temperature levels on the outer wall at the liner segment hook attachment area.

Thermocouples provided coverage of almost one complete quadrant of the full annular rig. Additional thermocouples were installed at a single circumferential position approximately opposite the instrumented quadrant. These second thermocouples provided temperature measurements that were used to confirm the data obtained from the primary quadrant sensors. Four instrumented, 0.2617 radian (15 degree) segments were available for each of the four liner regions: inner rear, inner front, outer rear, and outer front. The liner segments showing thermocouple locations are presented in Figures 5-3 through 5-6. The circumferential positions of the thermocouples are identified in Figure 5-7. As shown, the inner rear liner segment received the most extensive coverage.

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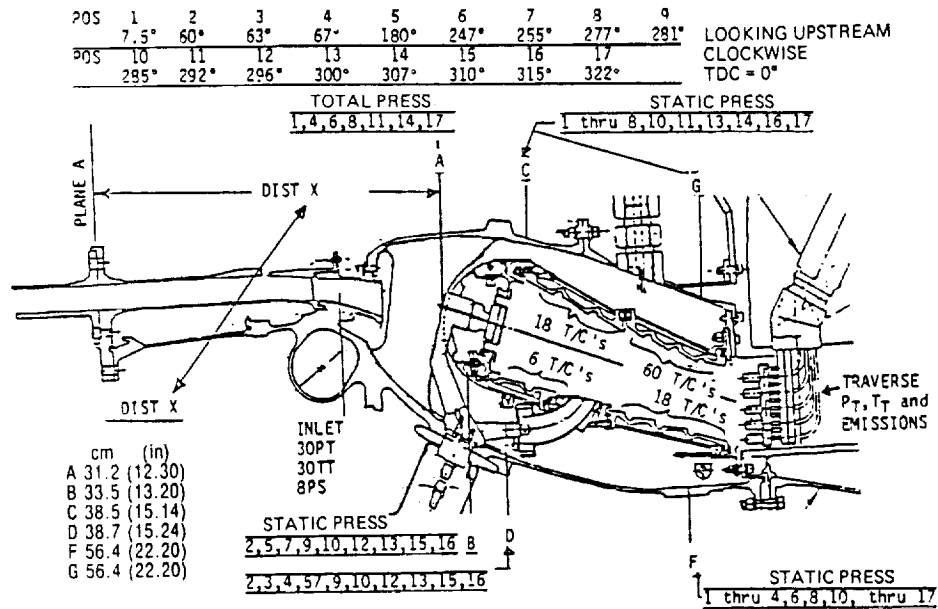


Figure 5-1 Full Annular Combustor Rig Component Instrumentation Map

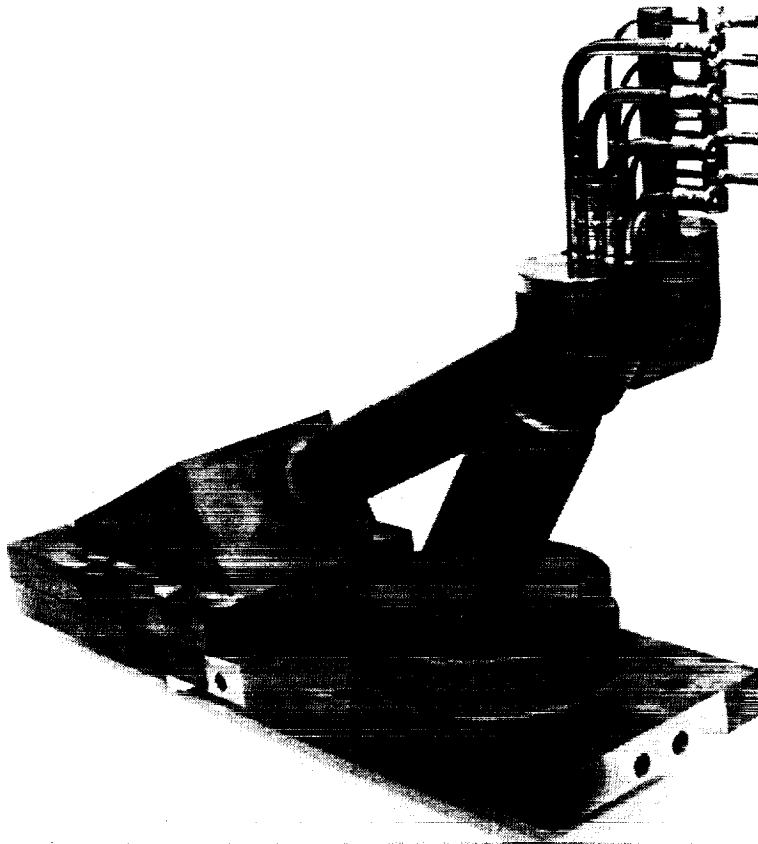


Figure 5-2. Total Pressure, Temperature and Emissions Probe Assemblies - Annular Combustor Test Rig

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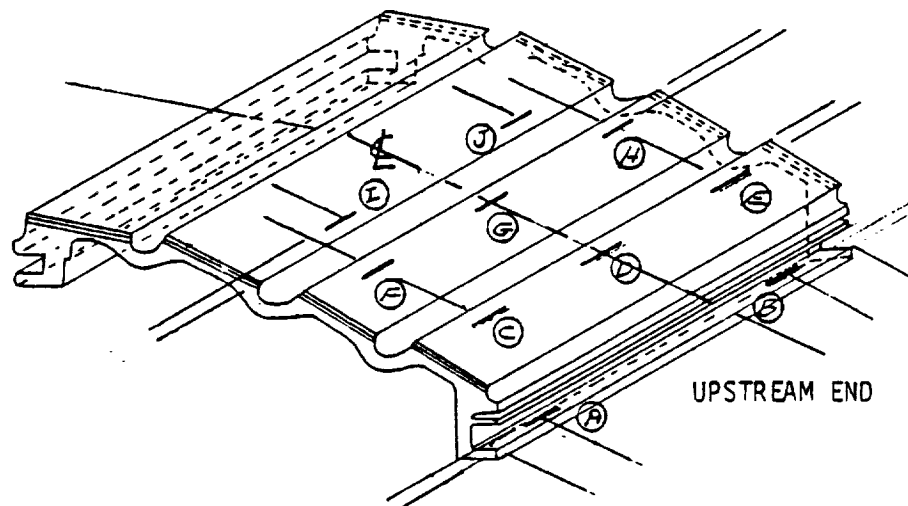


Figure 5-3 Inner Rear Liner Segment Thermocouple Locations

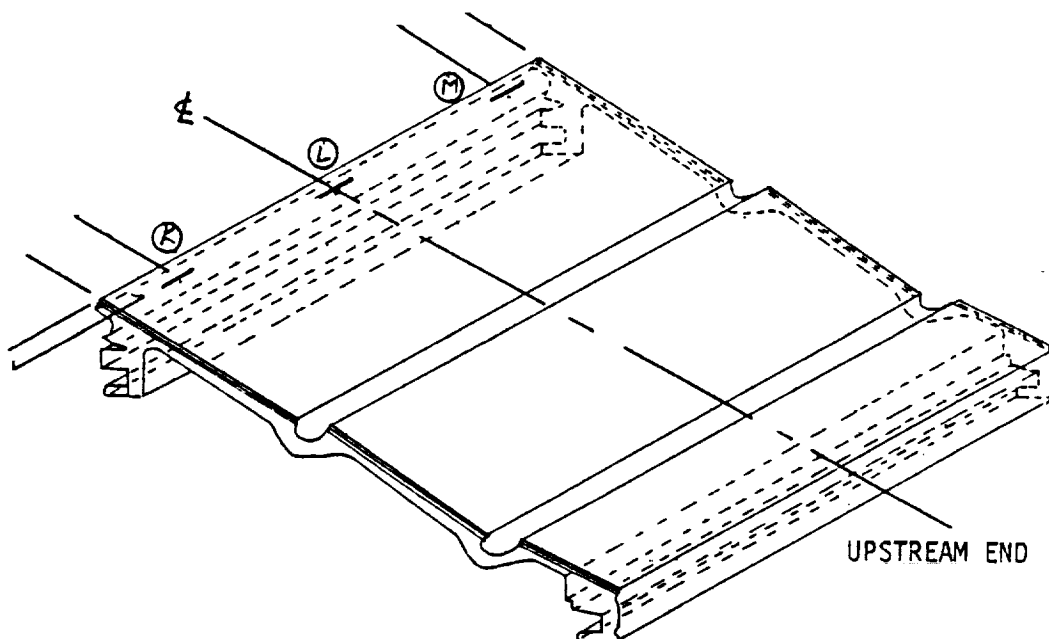


Figure 5-4 Inner Front Liner Segment Thermocouple Locations

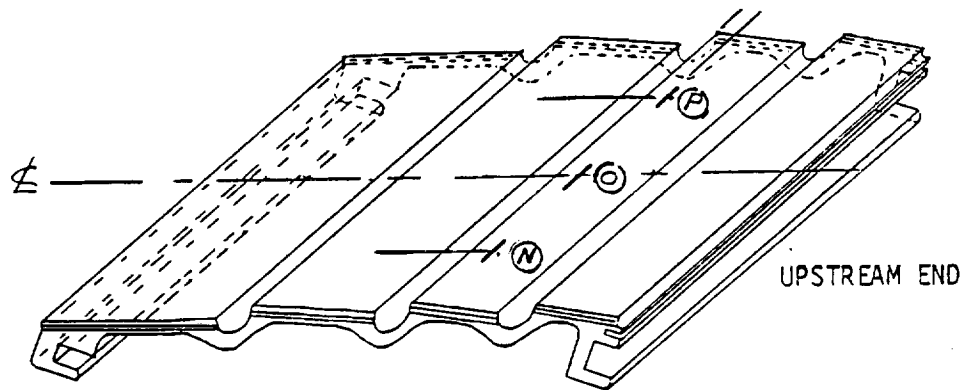


Figure 5-5 Outer Rear Liner Segment Thermocouple Locations

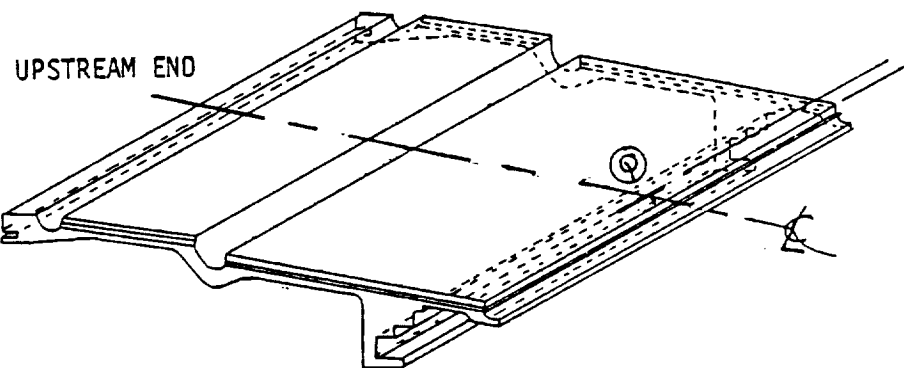
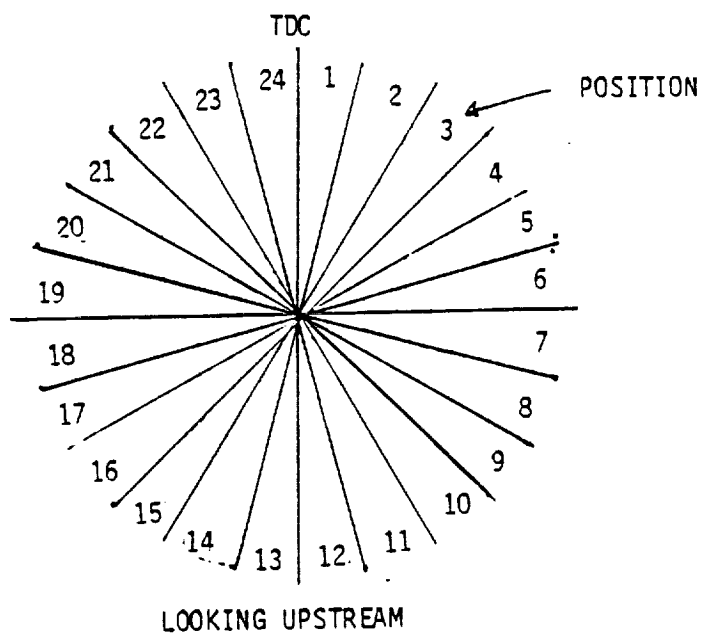


Figure 5-6 Outer Front Liner Segment Thermocouple Locations



Segment	ID	Circumferential Position					
		7	8	9	10	11	21
ID Rear	A	7A	8A	9A	10A	11A	21A
	B	7B	8B	9B	10B	11B	21B
	C	7C	8C	9C	10C	11C	21C
	D	7D	8D	9D	10D	11D	21D
	E	7E	8E	9E	10E	11E	21E
	F	7F	8F	9F	10F	11F	21F
	G	7G	8G	9G	10G	11G	21G
	H	7H	8H	9H	10H	11H	21H
	I	7I	8I	9I	10I	11I	21I
	J	7J	8J	9J	10J	11J	21J
ID Front	K	7K	8K	9K	10K	11K	21K
	L	7L	8L	9L	10L	11L	21L
	M	7M	8M	9M	10M	11M	21M
OD Rear	N	7N	8N	9N	10N	11N	21N
	O	7O	8O	9O	10O	11O	21O
	P	7P	8P	9P	10P	11P	21P
OD Front	Q	7Q	8Q	9Q	10Q	11Q	21Q

Figure 5-7 Segmented Liner Thermocouple Circumferential Positioning

Temperatures ranging up to 815°C (1500°F) were measured using calibrated thermocouples connected to reference junctions attached to uniform temperature reference blocks located in the test cells. The temperatures of these reference blocks were monitored relative to highly accurate electronic ice point cells calibrated to traceable standards of the National Bureau of Standards. Based on recent experience, a temperature measurement tolerance of  $\pm 0.139^\circ\text{C}$  ( $\pm 0.25^\circ\text{F}$ ) up to 260°C (500°F) and  $\pm 0.56^\circ\text{C}$  ( $\pm 1^\circ\text{F}$ ) up to 815°C (1500°F) can be expected for steady state data. Exit gas temperature measurement tolerance is  $\pm 0.5$  percent.

### 5.1.2 Combustor Sector Rig Instrumentation

#### 5.1.2.1 Performance Instrumentation

The instrumentation for the combustor sector rig performance test is presented in Table 5-II. Sufficient pressure and temperature probes were installed in the diffuser and combustion sections to completely document aerothermal performance.

Exit total pressures and temperatures were recorded by a stationary vane pack. Exhaust emissions and smoke samples were also obtained at the combustor exit using the vane pack. Figure 5-8 shows the vane pack. The exit probes were air cooled, and the gas sample lines were steam cooled. In addition, the gas sampling lines were manifolded so that emissions could be averaged radially or circumferentially. Since this system was essentially the same as the exit instrumentation in the full annular rig, the same pressure measurement tolerance of  $\pm 0.10$  percent could be assumed and the same calibration procedures used.

#### 5.1.2.2 Liner Temperature Sensors

To monitor liner overall thermal-mechanical performance, 10 imbedded thermocouples were installed on both the outer liners and inner liners of the sector rig. Thermal-sensitive paint was applied to selected liner panels to evaluate thermal gradients.

The thermocouples were of the same type used in the full annular rig (described in Section 5.1.1.2) and had the same accuracy.

## 5.2 TEST FACILITIES

The full annular and the combustor sector rig tests were conducted at the Pratt & Whitney Combustion Laboratory in Middletown, Connecticut. The full annular test was conducted at Stand X-960, and the sector test was conducted at Stand X-903.

TABLE 5-II  
COMBUSTOR SECTOR RIG PERFORMANCE INSTRUMENTATION

LOCATION	MEASUREMENT/TYPE	QUANTITY	PURPOSE
INLET	<ul style="list-style-type: none"> <li>o 4 ELEMENT TOTAL PRESSURE (<math>P_t</math>) PROBES</li> <li>o 4 ELEMENT TOTAL TEMPERATURE (<math>T_t</math>) PROBES</li> <li>o ID/OD WALL STATIC PRESSURE (<math>P_s</math>) TAPS</li> </ul>	<div>6</div> <div>5</div> <div>5/5</div>	<ul style="list-style-type: none"> <li>o RIG INLET <math>P_t/T_t</math> PROFILES</li> </ul>
PREDIFFUSER	<ul style="list-style-type: none"> <li>o ID WALL <math>P_s</math> TAPS (2 ROWS)</li> <li>o OD WALL <math>P_s</math> TAPS (2 ROWS)</li> </ul>	<div>6</div> <div>6</div>	<ul style="list-style-type: none"> <li>o PREDIFFUSER PERFORMANCE</li> </ul>
DIFFUSER CASE STRUTS	<ul style="list-style-type: none"> <li>o 5 LEADING EDGE <math>P_t</math>'s</li> </ul>	4 STRUTS	<ul style="list-style-type: none"> <li>o PREDIFFUSER EXIT PROFILE</li> </ul>
OUTER SHROUD	<ul style="list-style-type: none"> <li>o 2 ROWS WALL <math>P_s</math> TAPS</li> <li>o HC SNIFFER</li> </ul>	<div>4 EACH ROW</div> <div>1</div>	<ul style="list-style-type: none"> <li>o LINER FEED PRESSURE MAP</li> <li>o SAFETY</li> </ul>
INNER SHROUD	<ul style="list-style-type: none"> <li>o 2 ROWS WALL <math>P_s</math> TAPS</li> <li>o HC SNIFFER</li> </ul>	<div>6 EACH ROW</div> <div>1</div>	<ul style="list-style-type: none"> <li>o LINER FEED PRESSURE MAP</li> <li>o SAFETY</li> </ul>
COMBUSTOR HOOD	$P_s$ TAPS	2	<ul style="list-style-type: none"> <li>o BULKHEAD FEED PRESSURE</li> </ul>
EXIT	<ul style="list-style-type: none"> <li>o VANE PACK</li> <li>5 LEADING EDGE TC'S</li> <li>4 LEADING EDGE GAS SAMPLING PORTS</li> <li>5 <math>P_t</math> PORTS</li> </ul>	<div>8 VANES</div> <div>8 VANES</div> <div>4 VANES</div>	

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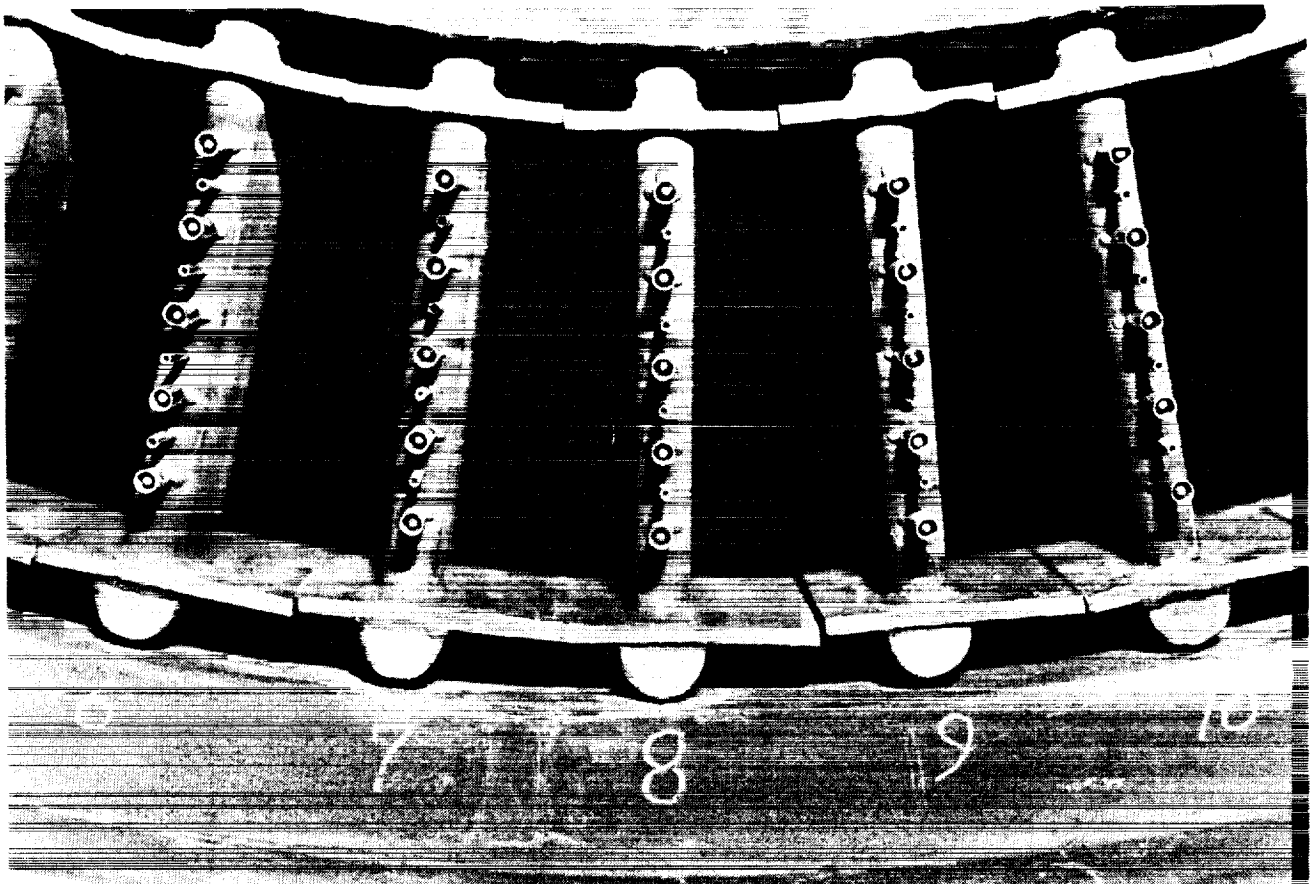


Figure 5-8 Vane Packs for Recording Combustor Sector Rig Exit Pressures, Temperatures, and Emissions

### 5.2.1 Full Annular Combustor Performance Rig Facility (X-960)

The X-960 facility is shown schematically in Figure 5-9 and its capabilities are listed in Table 5-III.

The test rig was contained within a cylindrical pressure tank with quick-disconnect breech lock seals that provided easy access to the rig for repair or modification. The test rig tank module was removable from the facility test cell center line as a self contained unit enabling assembly and instrumentation work to be performed away from the stand.

The control room, located immediately adjacent to the stand, contained all of the equipment to operate the rig. A supervisory control system was used to control rig operation and maintain test parameters. This system was controlled by a digital computer. Pertinent input signals were compared with preprogrammed levels within the computer, and the facility was trimmed as required. In addition to setting test conditions, the system controlled the rig during transients between test points and monitored the rig and facility safety parameters.

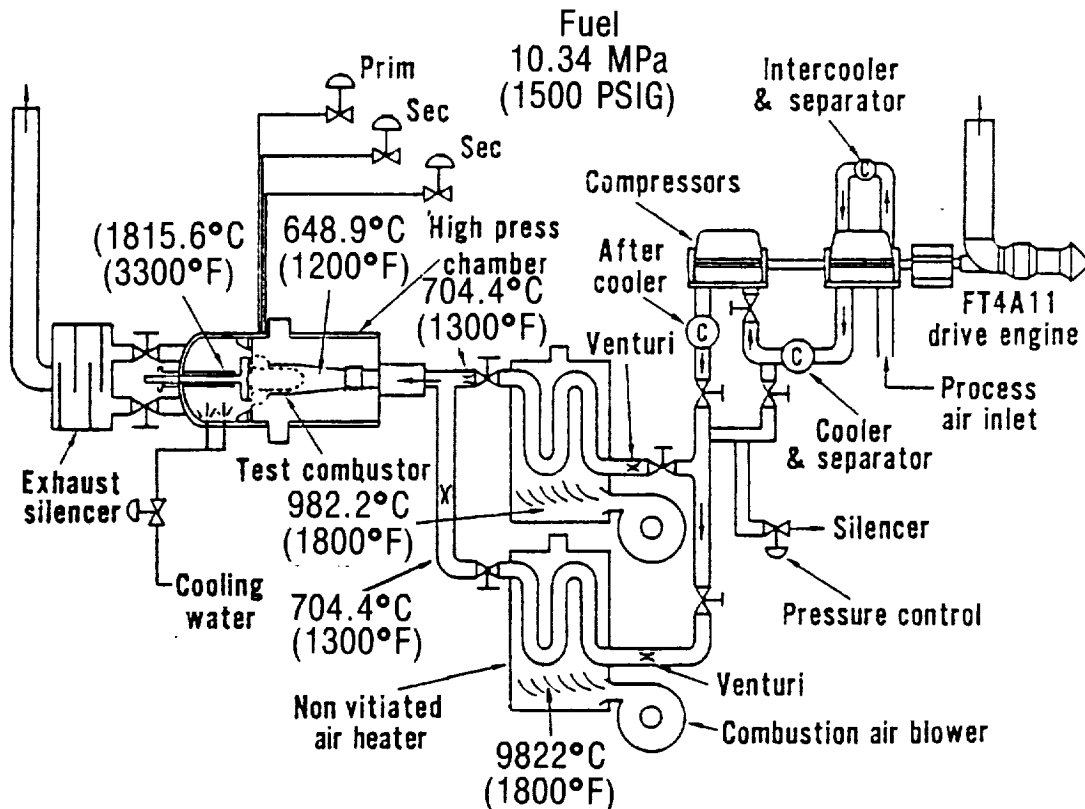


Figure 5-9 Full Annular Combustor Rig Facility Schematic (X-960)

TABLE 5-III  
FULL ANNULAR COMBUSTOR RIG FACILITY (X-960) CAPABILITIES

---

<u>PROCESS AIR SYSTEM*</u>	
Rated airflow:	45 kg/sec (100 lb/sec) at 4.482 MPa (650 psia)
Inlet temperature:	85°C (185°F) to 648°C (1200°F)
<u>SUPPLEMENTARY AIR SYSTEM*:</u>	
	11 kg/sec (25 lb/sec) at 4.482 MPa (650 psia)
<u>FULL SYSTEM:</u>	
	166 lpm (44 gpm) at 10.342 MPa (1500 psia) - Jet A or special fuels
<u>CHAMBER CAPABILITIES</u>	
Chamber diameter (ID):	1.83 m (6 ft - 0 in.)
Rig discharge temperature:	1815°C (3300°F)
<u>DATA ACQUISITION AND REDUCTION SYSTEMS</u>	
Steady state:	1600 channels-temperatures, pressures, flows
Emissions measuring instrumentation:	Meets federal (EPA) requirements
Data reduction:	On-line Univac computer
<hr/> * Nonvitiated	

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#### 5.2.2 Combustor Sector Performance Rig Facility (Stand X-903)

This facility provided nonvitiated inlet air at temperatures to 648°C (1200°F), airflows to 11 kg/sec (25 lb/sec), and pressures to 4.309 MPa (625 psia).

A wide range of fuels, including Jet-A, were available at pressures up to 10.342 MPa (1500 psia) and flow rates to 0.6 kg/sec (1.5 lb/sec). Fuel flow measurements were obtained by using multiple turbine flowmeters in each fuel line.

Secondary services included high pressure cooling water, steam, air, and inert gas purge systems and various electric power supplies.

The test rig was mounted within a cylindrical pressure tank where pressure was automatically controlled to 41,368 Pa (6 psi) above rig pressure. In this manner, the gas pressure load was supported by the facility pressure vessel permitting the experimental hardware to be of relatively light construction.

The thermal load was carried by the test rig. The main tank was cooled with an amount of purge air equal to 5 percent to 10 percent of combustor inlet airflow. A retractable tank section with a quick-disconnect breech-lock seal was provided enabling easy access to the rig.

### 5.2.3 Data Acquisition Systems

Both the X-960 and X-903 stands were equipped with automated data acquisition and recording systems. All data required for analysis were recorded and processed in real time by a large, digital, automatic data reduction computer (Univac). Raw data were transmitted in terms of counts or millivolts from the test facility to the computer center where it was reduced, converted to engineering units, and displayed on a scope.

Both stands had separate, continuously available emissions and smoke measurement systems. The emissions instrumentation and sample-handling systems were designed to conform to specifications in SAE ARP-1256. The following emissions data were obtained.

Carbon dioxide and carbon monoxide were measured with nondispersive infrared (NDIR) instruments (Beckman Model 865 in X-960 and Model 315A in X-903).

Total unburned hydrocarbons were measured with a Beckman Model 402 heated flame ionization detector (both stands).

Nitric oxide and total oxides of nitrogen were measured with a TECO Model 14D Chemiluminescence analyzer (both stands).

Oxygen was measured with a Scott Model 250 Paramagnetic  $O_2$  Analyzer in Stand X-960 and with a Beckman Model 715 analyzer using an amperometric probe in Stand X-903.

The combustor rig exhaust gas sample was distributed to the various instruments, with each instrument having its own flow metering system. Sample handling is shown schematically in Figure 5-10.

Three systems were available for data logging. The first system consisted of two Texas Instruments four-pen recorders that monitored the output of the instruments and provided a continuous real time record for either immediate inspection or subsequent analysis. The second system, a Tektronix digital magnetic tape cartridge recorder (Stand X-960) or punch paper tape (Stand X-903), recorded data on command for storage or later processing on an IBM 370 computer. The third system was an on-line Univac that provided essentially real time data recording and analysis. Data were either visually presented or printed.

A complete set of standard gases was continuously available. Combustor exhaust smoke measurements were obtained through a smoke measuring system that conformed to specifications of the Society of Automotive Engineers Aerospace Recommended Practice, ARP-1179.

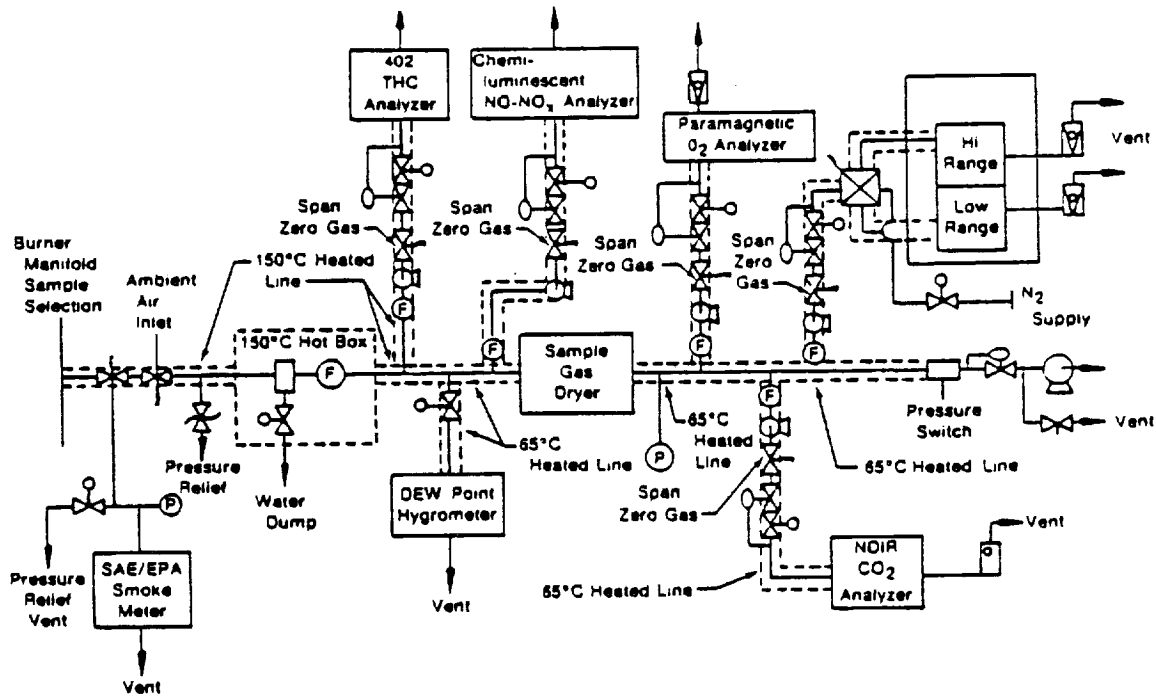


Figure 5-10 Emissions Measuring System Schematic

## SECTION 6.0 COMBUSTOR PERFORMANCE TEST RESULTS

### 6.1 FULL ANNULAR COMBUSTOR PERFORMANCE RIG TEST RESULTS

Performance and emissions results obtained during the full annular rig test are summarized in Table 6-I. The overall pressure loss goal of 5.5 percent was slightly exceeded because of an increase in inner and outer liner pressure losses that resulted when three rows of dilution air holes were eliminated from the design which increased the velocity over the downstream liner segments. The pressure drop across the inner and outer liners was a balanced 2.9 percent. This is slightly different than the previous results from the Supporting Technology Rig results, with the sheet metal carburetor tube combustor, where the inner liner pressure drop exceeded the outer passage by 0.2-0.3 percent. This minor difference was attributed to differences between sector to annular rigs, changes in the inner to outer passage flow splits and the possible difference in the placement of the combustor hood relative to the prediffuser exit.

TABLE 6-I  
FULL ANNULAR COMBUSTOR PERFORMANCE SUMMARY

<u>Pressure Loss</u> <u>% Pt3 (Goal)</u>	<u>Environmental Protection</u> <u>Agency Parameter (EPAP)</u>	<u>Emission Level</u>	
		<u>Goal</u>	<u>Test</u>
Overall: 5.8 (5.5)	Unburned Hydrocarbons	0.40	0.88
Outer Liner: 2.9	Carbon Monoxide	3.0	5.6
Inner Liner: 2.9	Oxides of Nitrogen	3.0	4.88
	Smoke Number	< 20.0	1.00
<u>Pilot Fuel Air Ratio</u>		<u>Resulting Pattern Factor (Goal)</u>	
0.0062		0.26 (0.37 Max)	
0.0034		0.30 (0.37 Max)	

The radial exit temperature profile (Figure 6-1) was comparable to that achieved in the sector rig tests with sheet metal carburetor tube combustor. Temperatures were slightly higher along the outer wall and slightly lower near the inner wall. This was the first indication of a difference in penetration of the fuel-air mixtures from the sheet metal carburetor tubes versus the cast versions employed in the component program.

The goal profile was achieved. Also, pattern factors were below the goal for the two pilot-to-main zone fuel splits evaluated. Circumferential variation of exit temperature characteristics at the peak location, 48 percent span, is presented in Figure 6-2. The peak values are generally associated with the main zone carburetor tubes but the overall levels are low. It should be noted that the temperature signature is normalized to the local span average. To obtain the corresponding actual profile factors data, Figures 6-1 and 6-2 can be combined algebraically in the following manner:

$$\frac{T - T_{4 \text{ avg}}}{T_{4 \text{ avg}} - T_3} = \left[ \frac{T_{\text{Local}} - T_{4 \text{ avg}}}{T_{4 \text{ avg}} - T_3} \right]^* + \left[ \frac{T - T_{\text{Local}}}{T_{\text{Local}} - T_3} \right]^{**} +$$

$$\left[ \frac{T_{\text{Local}} - T_{4 \text{ avg}}}{T_{4 \text{ avg}} - T_3} \right]^* \left[ \frac{T - T_{\text{Local}}}{T_{\text{Local}} - T_3} \right]^{**}$$

\*Taken from Figure 6-1

\*\*Taken from Figure 6-2

	Condition	Pilot F/A	Overall F/A
● Sector Rig	Climb	.0037	.018
□ Full Annular Rig	SLTO	.0062	.022
△ Full Annular Rig	SLTO	.0032	.022

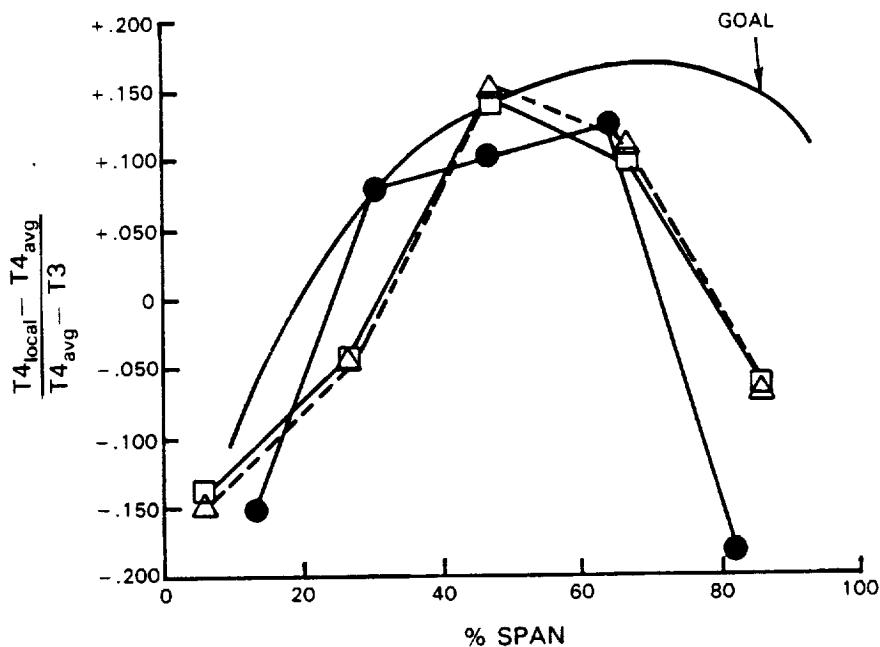


Figure 6-1 Combustor Radial Exit Temperature Profile Comparison - Full Annular Combustor Rig and Sector Rig with Sheet Metal Carburetor Tube Combustor

The higher pilot-main fuel split (pilot fuel/air ratio of 0.0062) produced a slightly lower pattern factor.

The full annular combustor rig had higher airflow percentages in both the pilot fuel injectors and main zone carburetor tubes than had been exhibited during the Supporting Technology Program tests. Figure 6-3 compares the airflow distribution in the full annular rig with those measured during the Supporting Technology Program.

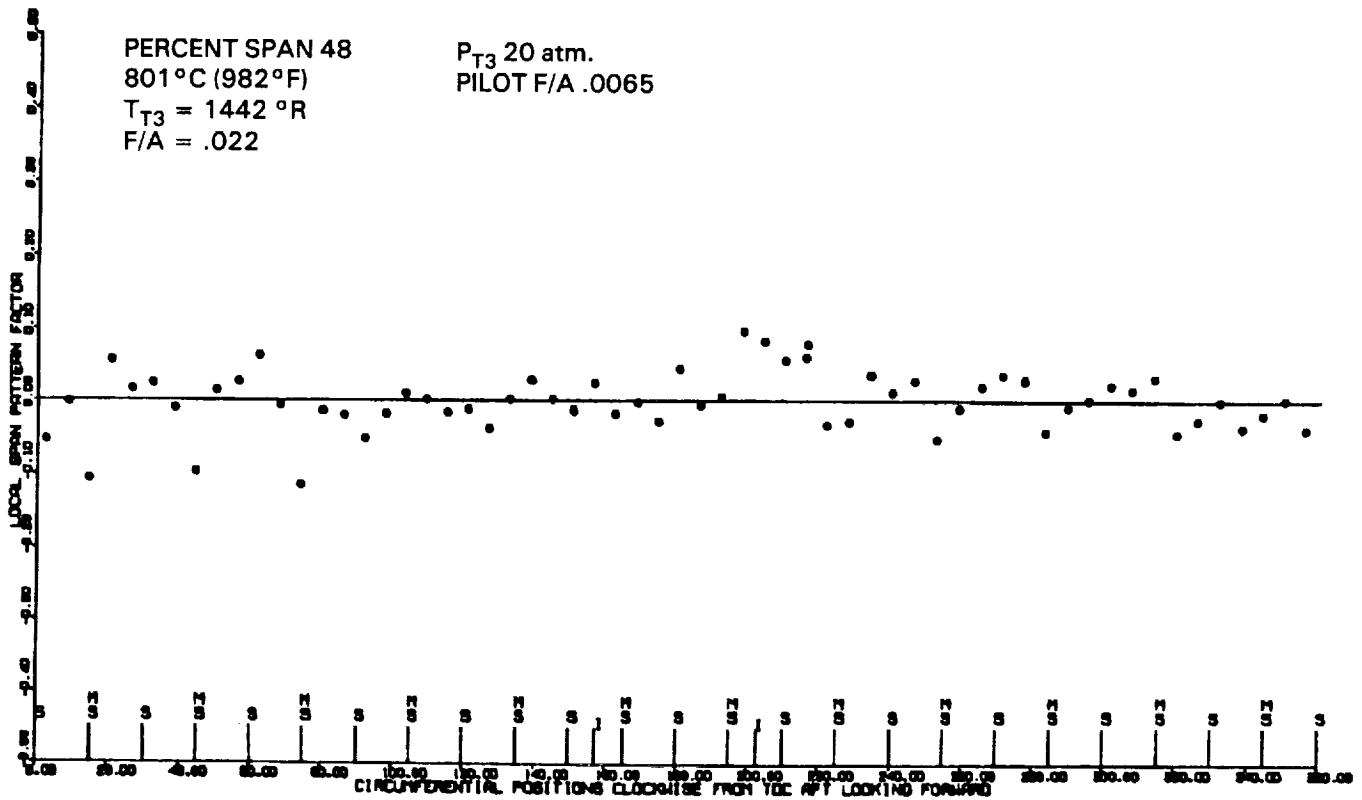
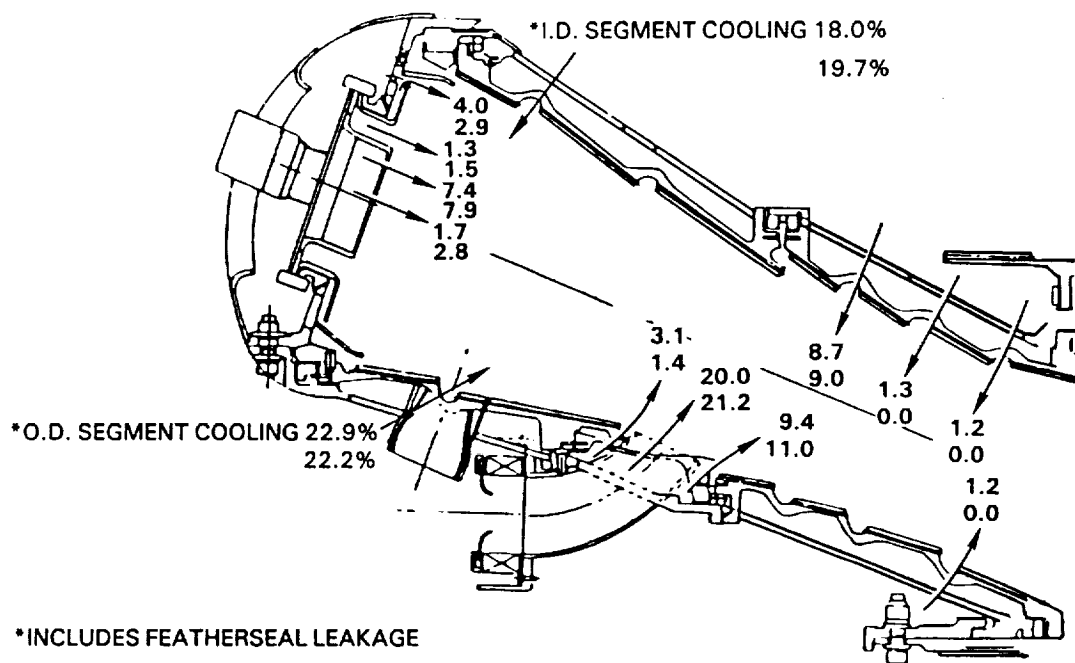


Figure 6-2 Energy Efficient Engine Full Annular Rig Exit Rake Circumferential Temperature Profile



Top Numbers Represent Supporting Technology Sector Rig Values; Bottom Numbers Represent Full Annular Rig Values

Figure 6-3 Comparison of Combustor Airflow Distribution - Full Annular Combustor Rig and Sector Rig with Sheet Metal Carburetor Tube Combustor

The carbon monoxide (CO) and unburned hydrocarbon (THC) emission trends exhibited during the full annular rig test at the idle operating condition are compared in Figure 6-4 with those exhibited by the sector rig with the sheet metal carburetor tube combustor during the Supporting Technology Program. Carbon monoxide and THC levels increased approximately 50 percent compared with those demonstrated during the Supporting Technology Program. This result is indicative of a lean primary zone. In addition, CO and THC levels also increased significantly at the approach condition. The increases shown in Figure 6-5 were probably due to the higher flowing carburetor tubes used during the full annular test. High power NO<sub>x</sub> emission characteristics presented in Figure 6-6 which show an approximately 15 percent reduction is also consistent with a leaner operating carburetor tube.

An inspection of the combustor at the end of testing showed no evidence of thermal distress. Figure 6-7 shows the excellent condition of the combustor bulkhead. A post-test thermal-paint analysis of the combustor liners revealed no significant high temperature streaks. Figures 6-8 and 6-9 show the typical post-test condition of the inner and outer liners, respectively. The hottest areas were along the feather seals on both the outer and inner liners. Although temperature levels were significantly lower, streak locations and patterns were similar to those exhibited during the Supporting Technology Program tests. Liner thermocouple data indicated that the wall temperatures were insensitive to the pilot/main zone fuel flow splits. Comparison to data from similar locations in the sector rig are presented in Figure 6-10. Both the maximum readings and the average of six segments are shown in relationship to observations in the sector rig. The levels and response to fuel-air ratio increases are slightly lower than sector rig results. The reduction in liner temperature levels was confirmed at full operating conditions during the sector rig performance testing of cast carburetor tube configuration discussed in the following section.

## 6.2 SECTOR RIG PERFORMANCE TEST

Performance testing with the sector rig configuration was directed at obtaining baseline emissions, performance, and liner temperature data with the cast carburetor tubes. The primary objective was to obtain additional data to improve understanding of the reasons for the increase in CO and THC emissions at the approach condition and the decrease in maximum liner temperatures observed during the full annular performance test. Since the substitution of the cast carburetor tube was the only significant modification introduced, a direct comparison with previous sector rig results was possible.

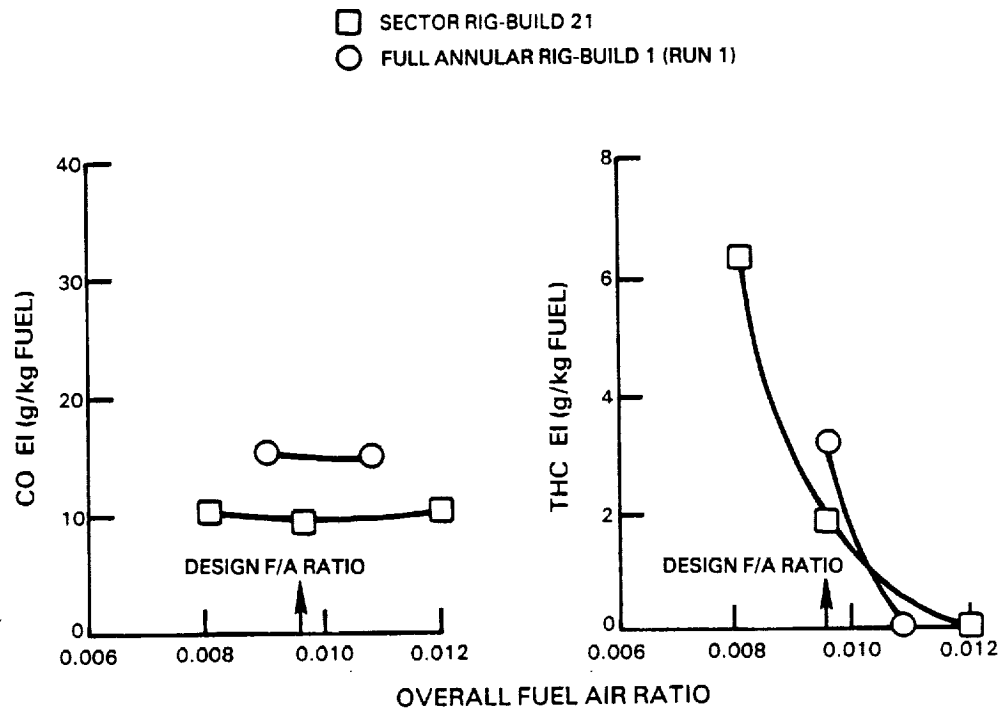


Figure 6-4 Carbon Monoxide and Unburned Hydrocarbon Idle Power Emission Trends Comparison - Full Annular Combustor Rig and Sector Rig with Sheet Metal Carburetor Tube Combustor

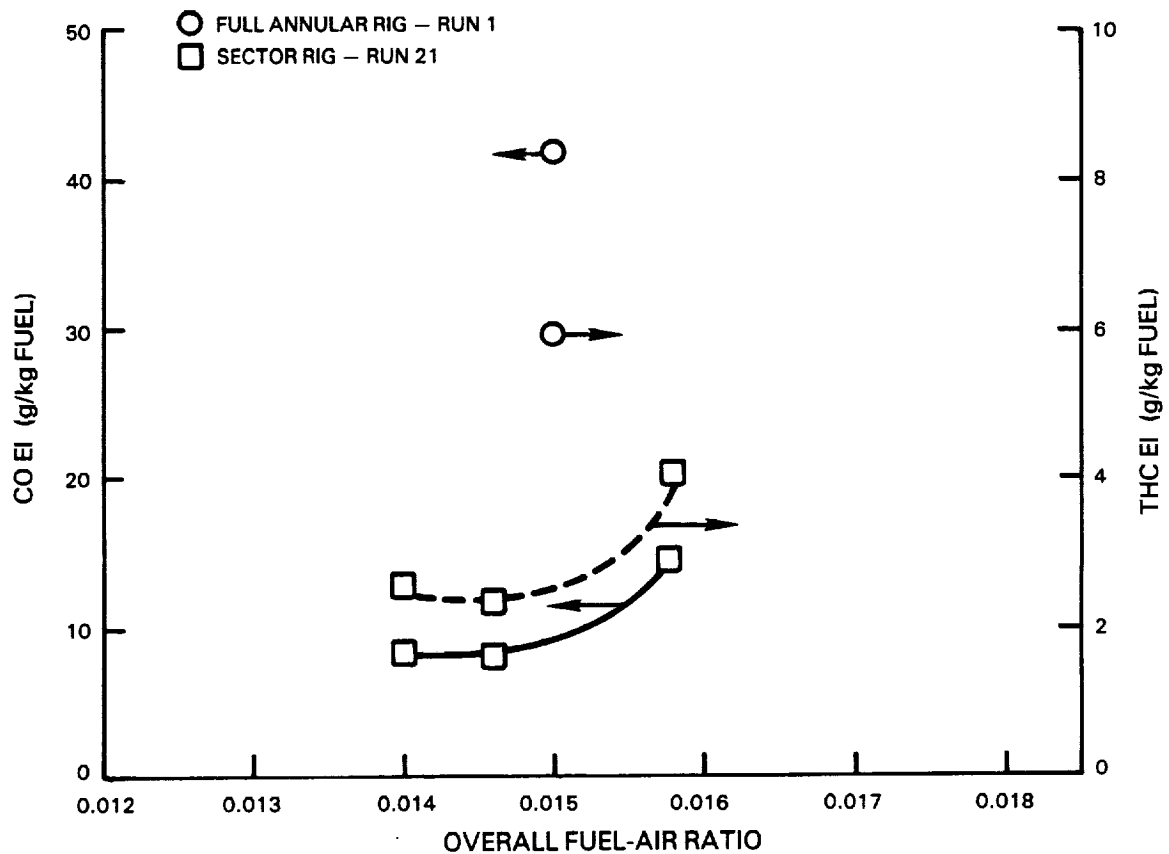


Figure 6-5 Comparison of Approach Emissions

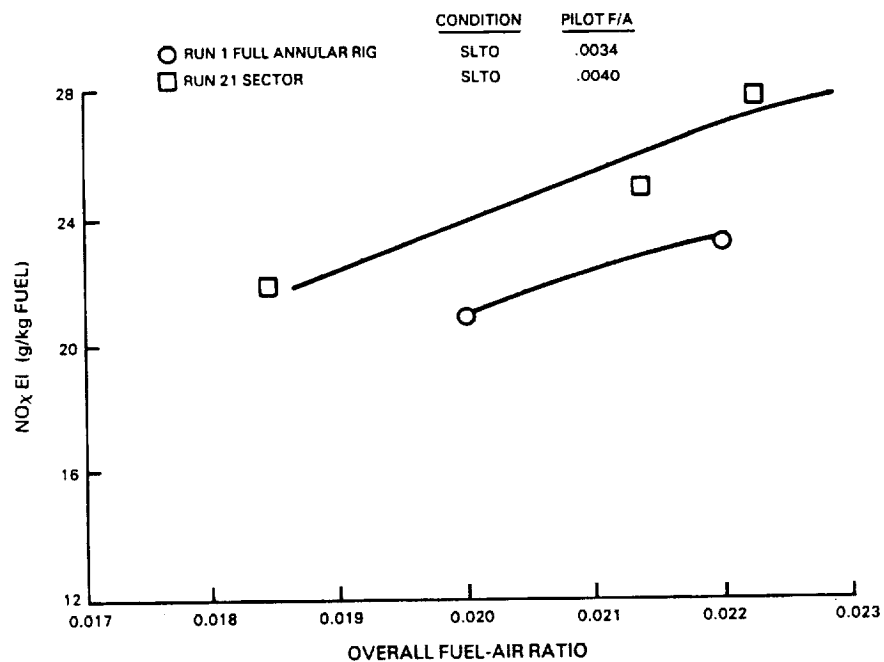


Figure 6-6 Variation of NO<sub>x</sub> With Fuel Air

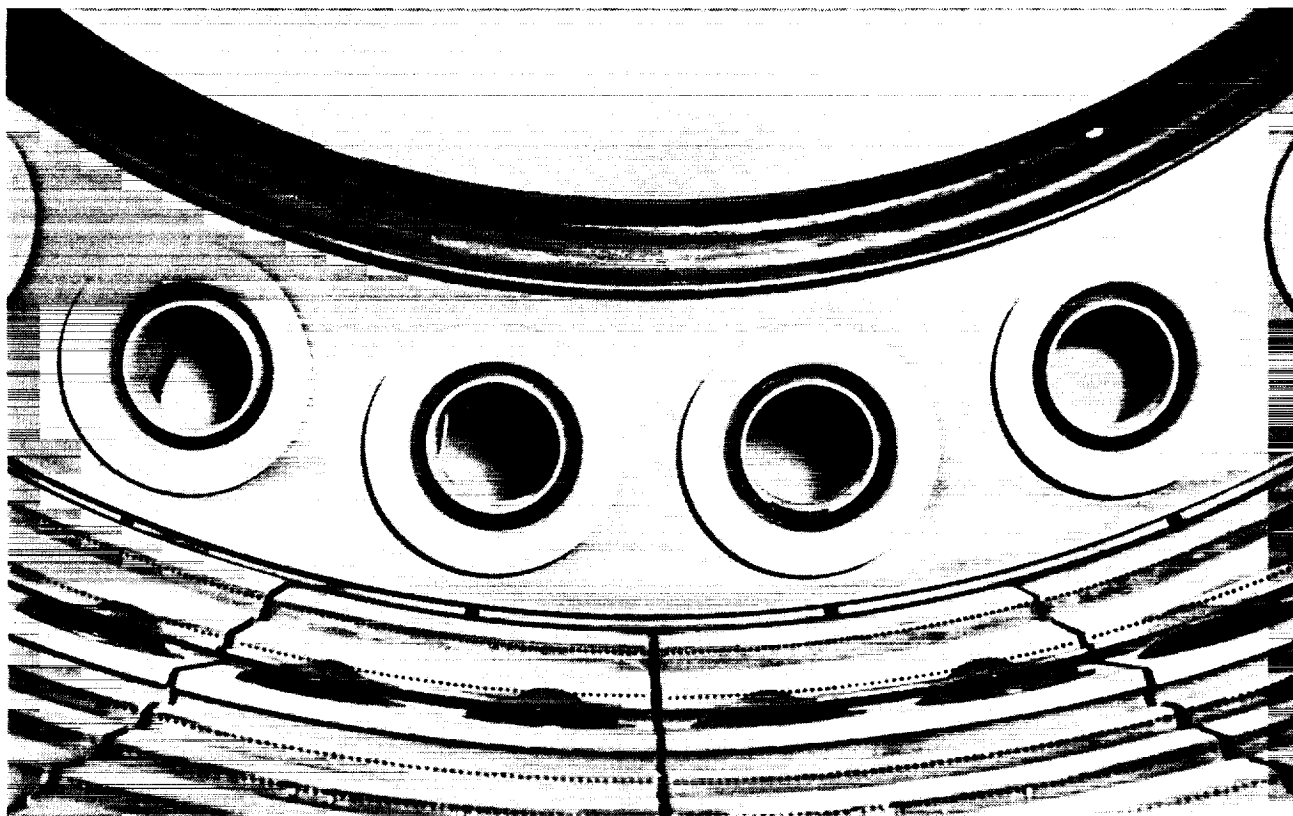


Figure 6-7 Post-Test Condition of Full Annular Combustor Bulkhead

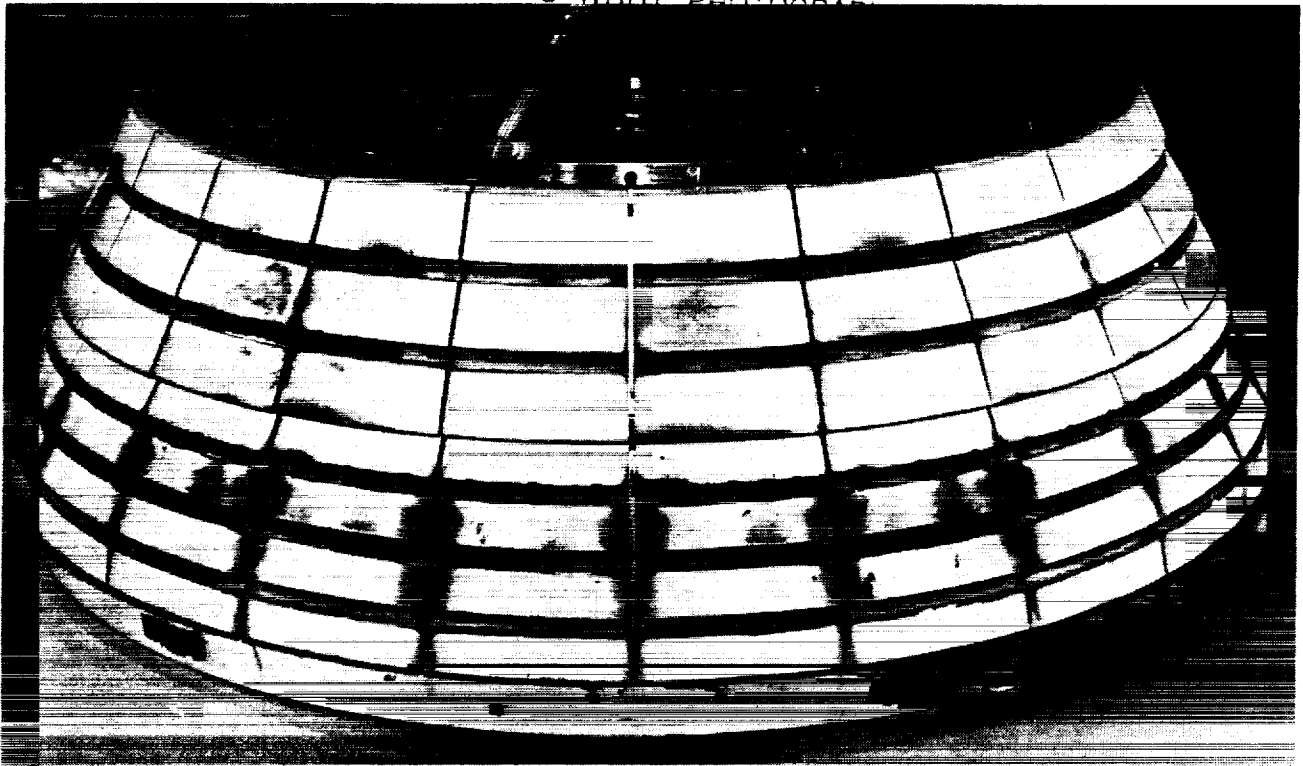


Figure 6-8 Post-Test Condition of Full Annular Combustor Inner Liner

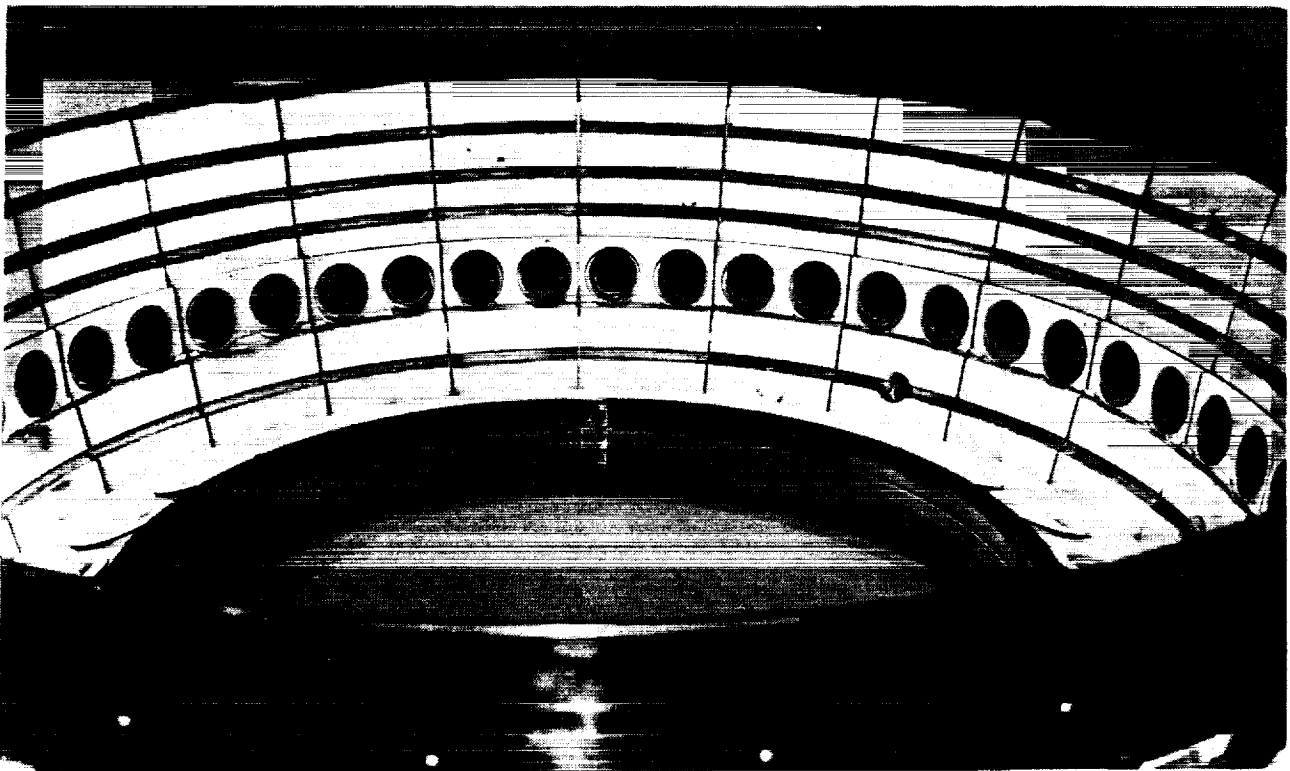


Figure 6-9 Post-Test Condition of Full Annular Combustor Outer Liner

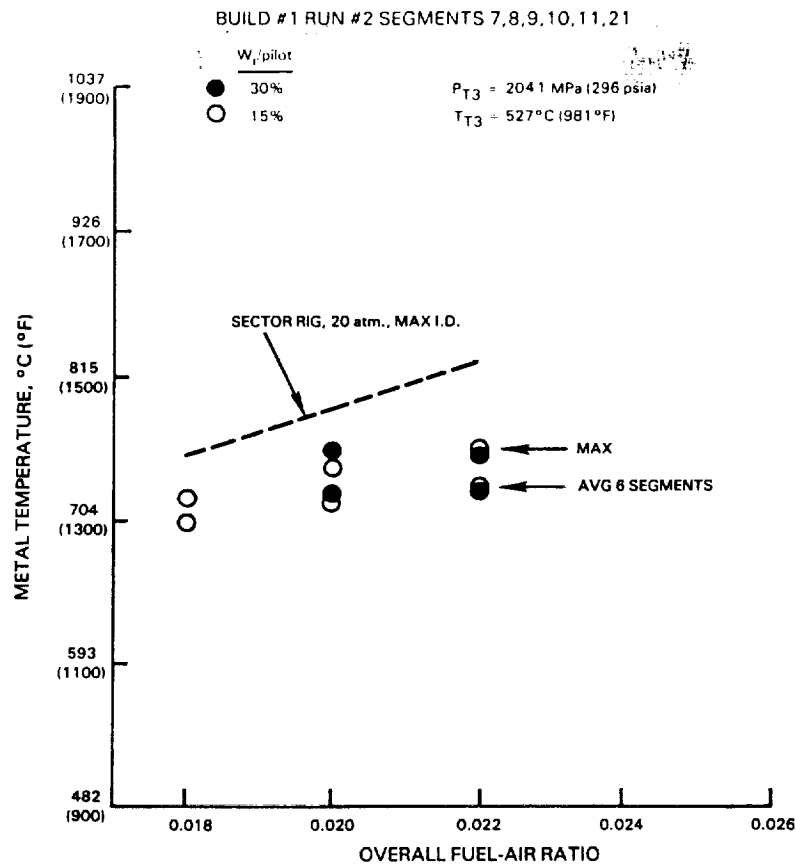


Figure 6-10 Energy Efficient Engine Full Annular Rig Liner Thermocouple Data

A Comparison of the original carburetor tube developed in the sector rig program with the cast version is shown schematically in Figure 6-11. The modifications were made in order to improve castability and to facilitate installation of the carburetor tubes. Design changes made, the reason for the change and the perceived risks are summarized below.

<u>Cast Tube</u>	<u>Reason</u>	<u>Risk</u>
o Increased secondary flow	Reduce $\text{NO}_x$ emissions	Fuel lean injector
o Remove annular scoop	Ease of installation	Non-uniform air feed pressure to axial swirler
o Increased wall thickness	Casting requirement	Deterioration in fuel droplet atomization
o Recessed axial swirler	Casting and installation requirement	Reduced swirl

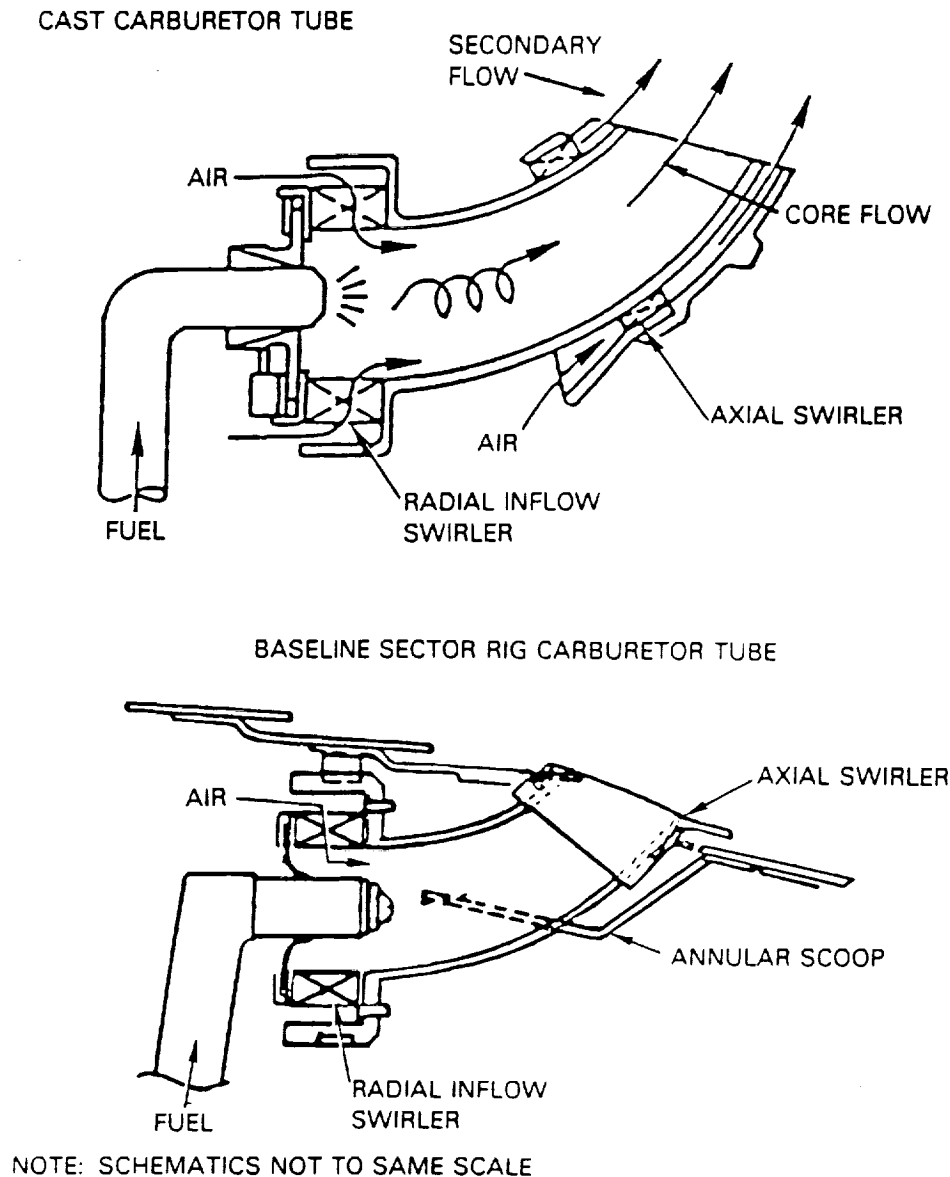


Figure 6-11 Comparison of Cast Component and Sheet Metal Sector Rig Carburetor Tubes

Significant increases in unburned hydrocarbons and carbon monoxide levels measured at combustor inlet conditions corresponding to engine approach conditions (30 percent of full takeoff power) tended to confirm the first and third risk items. To gain better insight to the problem, both types of main zone fuel injector assemblies were tested for air and fuel flow characteristics. Effective flow areas for both configurations were at the design levels and are summarized along with swirl strength measurements in Table 6-II.

TABLE 6-II  
CARBURETOR TUBE AIR FLOW TEST SUMMARY

	ACd cm <sup>2</sup> (in <sup>2</sup> )		Swirl Strength* - cm (in)
	Core	Secondary	
Sheet Metal	1.74 (0.27)	0.645 (0.10)	1.8-2.0 (0.7-0.8)
Cast	1.68 (0.26)	0.839 (0.13)	1.8-2.0 (0.7-0.8)

\*Swirl Strength = (Measured Torque)/(Measured Thrust) at Exit Plane

Fuel distributions along the minor axis of the ellipse formed at the exit of the two carburetor tubes are presented in Figure 6-12. The fuel film accumulation was distinctly asymmetric with the cast configuration. As expected, non-uniform filming of the fuel was also reflected in larger measured droplet sizes and broader droplet distributions (i.e., not monodispersed).

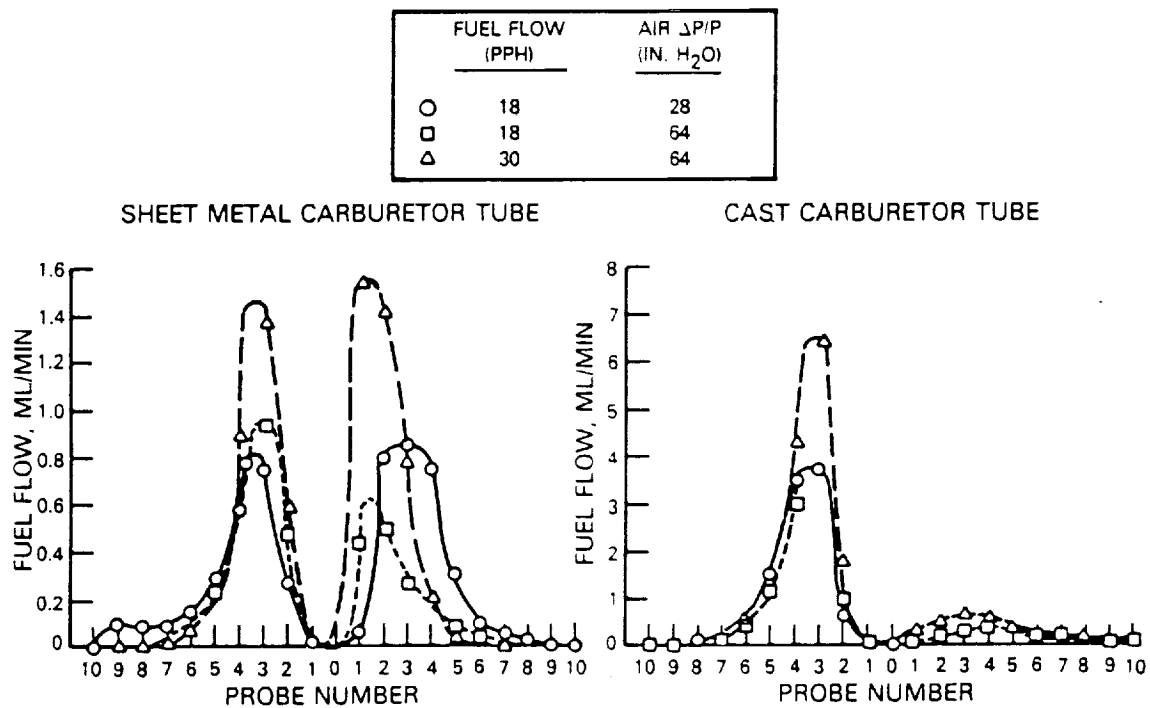


Figure 6-12 Comparison of Carburetor Tube Fuel Spray Characterization

The combustor airflow distribution from the sector rig tests for the Supporting Technology Program (build 21) and Combustor Component Performance Program (build 22) is shown in Figure 6-13. As had been expected, core and secondary airflows with the cast carburetor tubes were higher in build 22 than those obtained in build 21 with the sheet metal carburetor tubes. Carbon monoxide and THC emissions at the approach condition increased significantly (Figure 6-14) confirming that the high CO and THC emissions observed during the full annular performance rig test were a result of the higher-flowing carburetor tube. Subsequent airflow tests of the cast carburetor tubes modified to reduce secondary passage discharge area verified an increase in swirl strength. A revised carburetor tube casting was selected for use in the subsequent combustor sector rig evaluation testing of both an advanced cooling scheme for the segmented liner and the nonmetallic segmented liners.

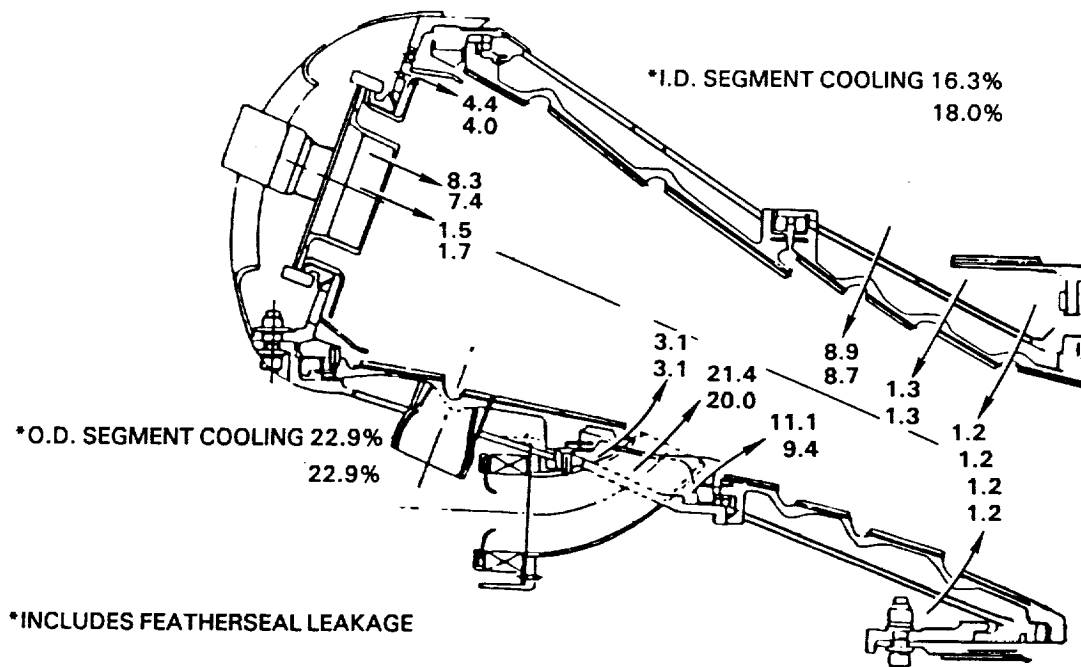


Figure 6-13 Comparison of Combustor Airflow Distribution -  
Combustor Sector Rig with Cast Carburetor Tubes and  
Sector Rig With Sheet Metal Carburetor Tube Combustor

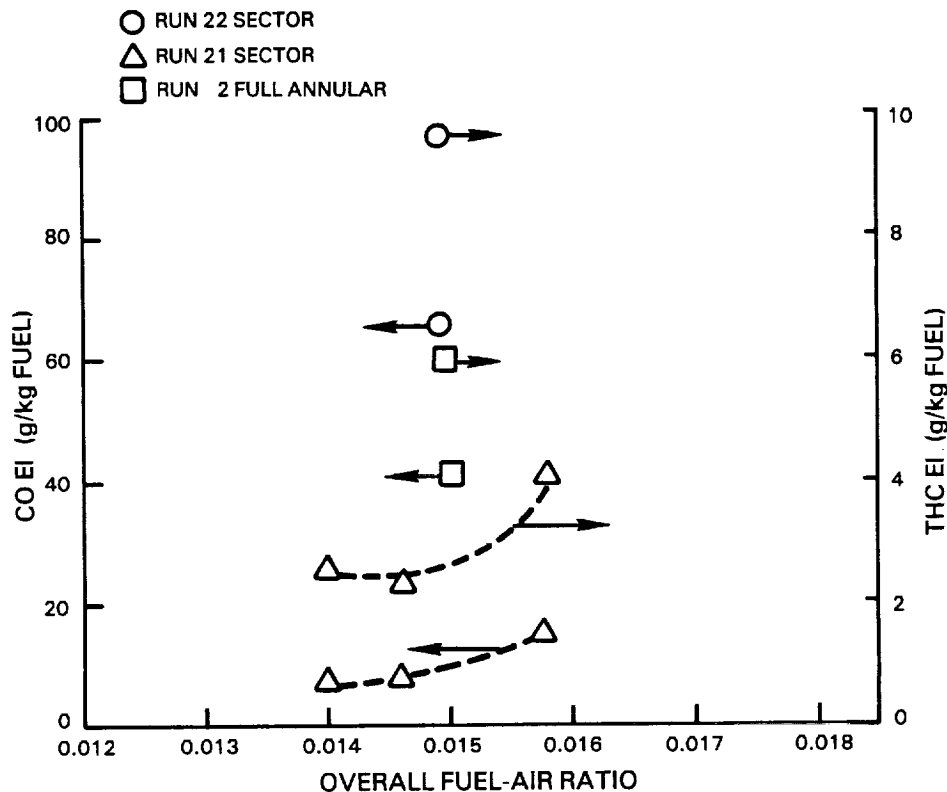


Figure 6-14 Comparison of Approach Emissions

Pattern factor increased as a result of the higher peaked exit radial temperature profile Figure 6-15, because of excess dilution air in the rearmost inner and outer liners. The profile would have been very similar to the full annular rig profile if the last three rows of dilution air holes had been utilized to reduce temperatures at the peak.

A post-test thermal-paint analysis showed that significant reductions in liner temperatures were achieved with the cast carburetor tube design. Figures 6-16 and 6-17 show the typical post-test condition of the inner and outer liners, respectively.

Main zone inner segment streak temperatures are compared in Figure 6-18. Temperatures at the segment axial edges were reduced as much as 111°C (200°F), and local hot spots were reduced by approximately 56°C (100°F). The maximum estimated liner temperature was 1037°C (1900°F) at the sea level takeoff (hot day) design point. Inner liner thermocouple data at two pressure levels indicate in Figure 6-19 up to 72°C (130°F) increase in wall temperature for an increase in pressure from 20 to 27 atmospheres. This was as a result of increase in the radiation heat load at the higher pressure level. The effect of pressure on wall temperature and flame radiation flux was a prime objective of the Pin Fin and Ceramic Composite Segmented Liner Combustor Sector Rig Test (Reference 4). A heavily thermocouple and radiometer instrumented sector rig was employed to measure various components of heat flux to the liner as a function of combustor operating parameters.

# AVERAGE EXIT RADIAL TEMPERATURE PROFILE

	<u>Condition</u>	<u>Pilot F/A</u>	<u>Performance F/A</u>
○ Sector Rig with Cast Carburetor Tubes	SLTO	.0036	.024
△ Sector Rig with Sheet Metal Carburetor Tubes	CLIMB	.0037	.018
□ Full Annular Rig	SLTO	.0032	.022

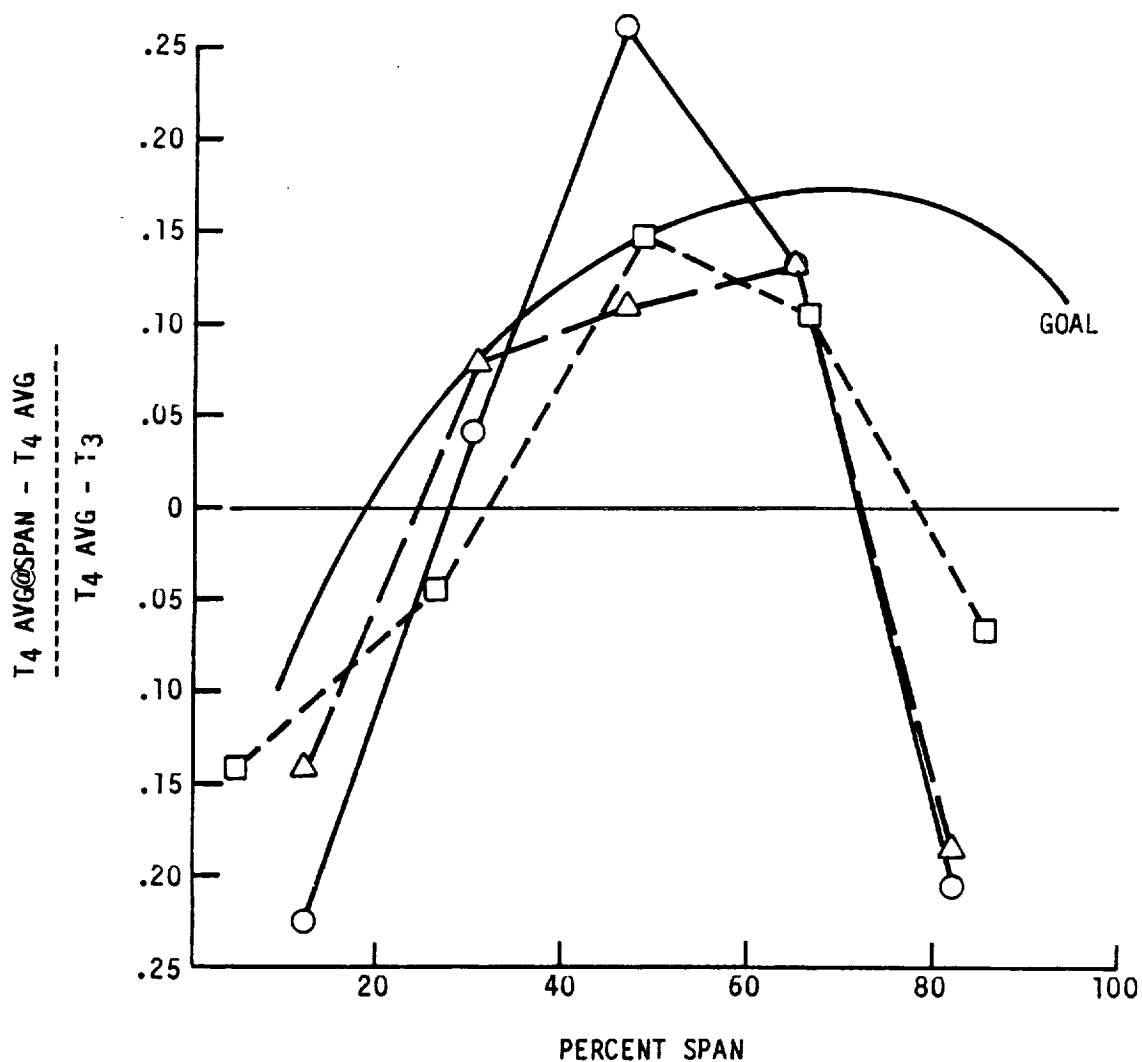


Figure 6-15 Combustor Sector Rig Exit Radial Temperature Characteristics Compared with Full Annular Rig and Sector Rig with Sheet Metal Carburetor Tube Combustor

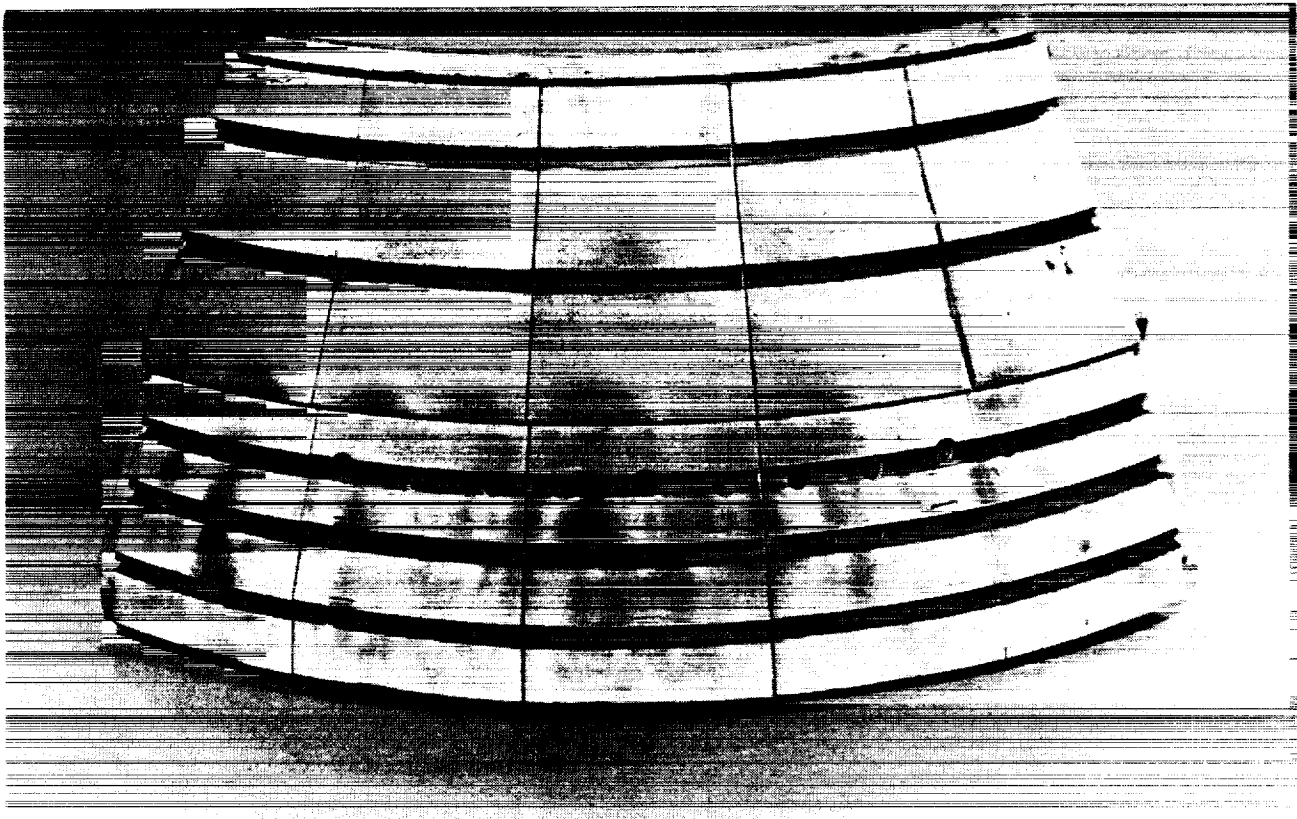


Figure 6-16 Post-Test Condition of Combustor Sector Rig Inner Liner

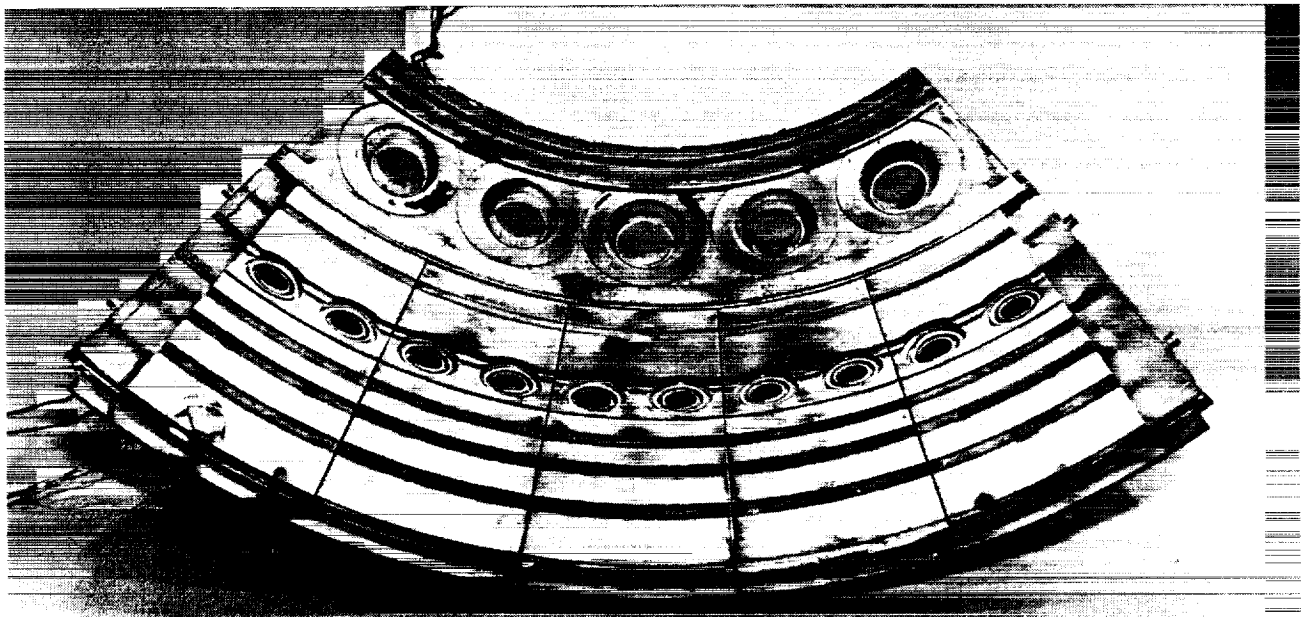


Figure 6-17 Post-Test Condition of Combustor Sector Rig Outer Liner

RUN 20

954-982 (1750-1800)

816-871 (1500-1600)

982-1038 (1800-1900)

982-1038 (1800-1900)

816-871 (1500-1600)

899-982 (1850-1800)

982-1038 (1800-1900)

816-871 (1500-1600)

954-1010 (1750-1850)

816-871 (1500-1600)

42

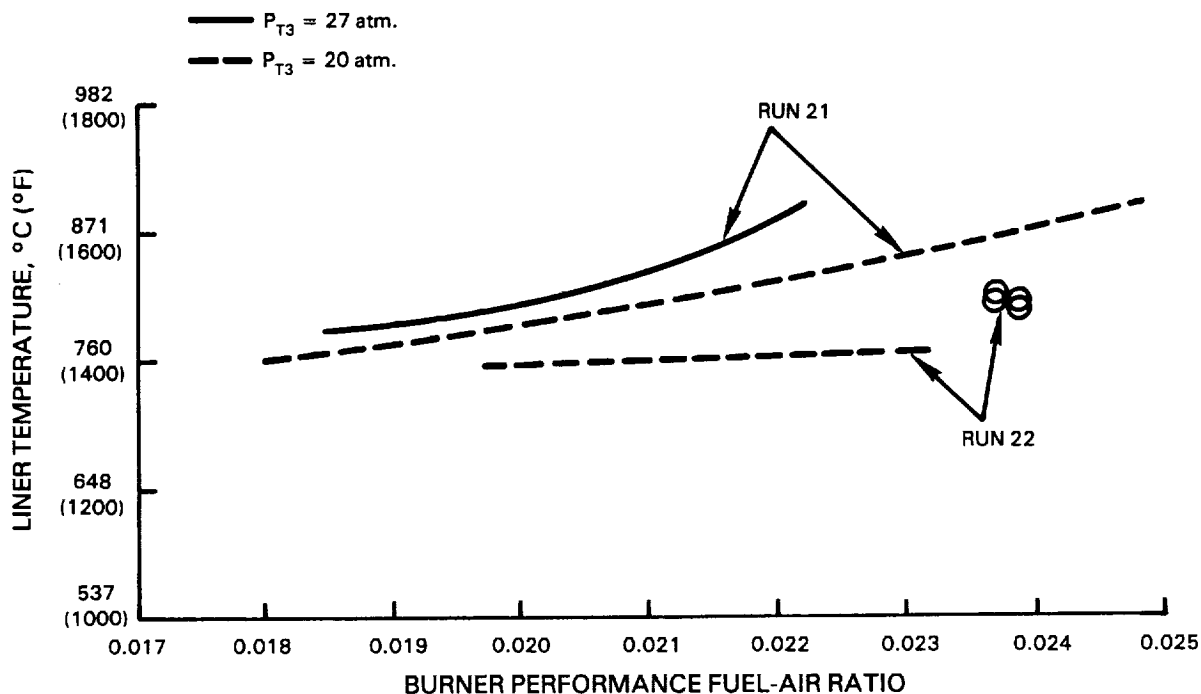


Figure 6-19 Comparison of Inner Liner Segment Thermocouple Maximum Temperatures Run 22 Versus Run 21

Main zone outer liner temperatures were the same for both sector rig tests. These temperatures were also equal to or below design values and were essentially streak free. The improved liner temperature patterns with the cast carburetor tubes were similar to those of the full annular rig performance test.

### 6.3 SUMMARY OF TEST RESULTS

Results of the full annular combustor rig tests for the Combustor Component Performance Program indicated that emissions and aerothermal performance trends were similar to those demonstrated during the preceding sector rig tests for the Support Technology Program.

Results from post-test analyses of the combustor sector rig indicated an unsatisfactory increase in fuel system carburetor tube core and secondary airflows and, as a result, an increase in CO and THC emissions. The increased airflows are directly attributable to the cast carburetor tube design. Also noted during the full annular rig performance test, and confirmed by the following sector rig performance test, were reduced inner liner temperatures which are also related to the use of cast carburetor tubes. Outer liner temperatures were the same for both rig tests.

Carburetor tube modifications were subsequently made to reduce secondary airflow and to provide the desired performance characteristics. Modified carburetor tubes were also evaluated in the combustor sector rig. The test results of this configuration imply that previously demonstrated emissions performance levels could be achieved with reduced flow cast carburetor tube.

## NOMENCLATURE

TOBI	Tangential-On-Board Injection System
EPA	Environmental Protection Agency
PT	Total Pressure
TT	Total Temperature
TDC	Top Dead Center
T3	Compressor Exit Total Temperature
T4	Combustor Exit Total Temperature
$A_{cd}$	Effective Flow Area

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3. Roberts, R., Fiorentino, A., and Greene, W., "Experimental Clean Combustor Program Phase III Final Report", Pratt & Whitney, NASA CR-135253, October 1977.
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